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The Marginal Soils of Africa

Rethinking Uses, Management and
Reclamation



Springer

The Marginal Soils of Africa

Adornis Dakarai Nciizah • Ashira Roopnarain
Busiswa Ndaba • Mashapa Elvis Malobane
Editors

The Marginal Soils of Africa

Rethinking Uses, Management
and Reclamation

 Springer

Editors

Adornis Dakarai Nciizah
Natural Resources and Engineering
Agricultural Research Council
Pretoria, South Africa

Busiswa Ndaba
Institute for Catalysis and Energy Solutions,
College of Science, Engineering and
Technology
University of South Africa—Florida Campus
Florida, South Africa

Ashira Roopnarain
Microbiology and Environmental
Biotechnology Research Group,
Agricultural Research Council—Natural
Resources and Engineering
Pretoria, South Africa

Department of Environmental Sciences,
College of Agriculture and Environmental
Sciences
University of South Africa—
Florida Campus
Florida, South Africa

Mashapa Elvis Malobane
Dept. of Agriculture and Animal Health
University of South Africa
Florida, South Africa

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Contributors

M. Akindolire Agricultural Research Council—Natural Resources and Engineering, Pretoria, South Africa

Uchenna Aniakor Godfrey Okoye University, Enugu, Enugu State, Nigeria

Nadia Alcina Araya Agricultural Research Council—Vegetable, Industrial and Medicinal Plants, Irene, Pretoria, South Africa

Hintsa Tesfamicael Araya Agricultural Research Council—Vegetable, Industrial and Medicinal Plants, Irene, Pretoria, South Africa

Michael Bairu Agricultural Research Council—Vegetable, Industrial and Medicinal Plants, Irene, Pretoria, South Africa

T. L. Botha University of Johannesburg, Auckland Park, Johannesburg, South Africa

Tinashe Chavhunduka The Southern African Confederation of Agricultural Unions, Lyttelton, Centurion, Pretoria, South Africa

Ngavaite Chigede Department of Livestock, Wildlife and Fisheries, Gary Magadzire School of Agriculture, Great Zimbabwe University, Masvingo, Zimbabwe

Justin Chipomho Marondera University of Agricultural Sciences and Technology, Marondera, Zimbabwe

Parwada Cosmas Tugwi-Mukosi Multidisciplinary Research Institute (TMMRI), Midlands State University (MSU), Zvishavane, Zimbabwe

Christian Philippus Du Plooy Agricultural Research Council—Vegetable, Industrial and Medicinal Plants, Irene, Pretoria, South Africa

Ernest Dube School of Natural Resource Management, Nelson Mandela University, George, South Africa

Christabel Ene Godfrey Okoye University, Enugu, Enugu State, Nigeria

Morris Fanadzo Cape Peninsula University of Technology, Wellington, South Africa

S. M. Grobler Agricultural Research Council—Animal Production, Irene, Pretoria, South Africa

M. C. Hernandez-Soriano John Innes Centre, Norwich, UK

M. V. Kidson Agricultural Research Council—Natural Resources & Engineering, Pretoria, South Africa

Funso R. Kutu School of Agricultural Sciences, University of Mpumalanga, Mbombela, South Africa

M. R. Madzivhandila University of South Africa, Florida, South Africa

Rebecca Mahlangu Agricultural Research Council—Vegetable, Industrial and Medicinal Plants, Irene, Pretoria, South Africa

Manaka Makgato Agricultural Research Council—Infruitec-Nietvoorbij, Stellenbosch, South Africa

Fortunate Makore Department of Crop Science, Faculty of Plant and Animal Sciences and Technology, Marondera University of Agricultural Sciences and Technology, Marondera, Zimbabwe

Maria M. Makwela University of KwaZulu-Natal, College of Agriculture, Engineering, and Science, School of Life Science, Scottsville, South Africa

M. J. Malaka Agricultural Research Council—Vegetable, Industrial and Medicinal Plants, Pretoria, South Africa

Mashapa Elvis Malobane University of South Africa, Department of Agriculture and Animal Health, Florida, South Africa

Tshifhiwa Paris Mamphogoro Agricultural Research Council—Animal Production, Irene, Pretoria, South Africa

Beverly Mampholo Agricultural Research Council—Vegetable, Industrial and Medicinal Plants, Irene, Pretoria, South Africa

Sinalo Mani Agricultural Research Council—Animal Production, Irene, Pretoria, South Africa

Misi Amos Manyanga Department of Soil and Plant Sciences, Gary Magadzire School of Agriculture, Great Zimbabwe University, Masvingo, Zimbabwe

Jerikias Marumure Department of Physics, Geography and Environmental Sciences, School of Natural Sciences, Great Zimbabwe University, Masvingo, Zimbabwe

B. Mndzebele Agricultural Research Council—Natural Resources and Engineering, Pretoria, South Africa

Meshack Mofokeng Agricultural Research Council—Vegetable, Industrial and Medicinal Plants, Irene, Pretoria, South Africa

Salmina Mokgehle School of Agricultural Sciences, University of Mpumalanga, Mbombela, South Africa

Chimweta Moreblessing Department of Crop Science, Faculty of Plant and Animal Sciences and Technology, Marondera University of Agricultural Sciences and Technology, Marondera, Zimbabwe

M. G. Moremi Agricultural Research Council—Vegetable, Industrial and Medicinal Plants, Pretoria, South Africa

Thamsanqa D. E. Mpanza Agricultural Research Council—Animal Production, Irene, Pretoria, South Africa

Caroline Mubekaphi School of Natural Resource Management, Nelson Mandela University, George, South Africa

Michel Mubvuma Department of Soil and Plant Sciences, Gary Magadzire School of Agriculture, Great Zimbabwe University, Masvingo, Zimbabwe

Binganidzo Muchara University of South Africa, Graduate School of Business Leadership, Midrand, South Africa

Clarice Mudzengi Department of Livestock, Wildlife and Fisheries, Gary Magadzire School of Agriculture, Great Zimbabwe University, Masvingo, Zimbabwe

Hupenyu A. Mupambwa Sam Nujoma Marine and Coastal Resources Research Center, Sam Nujoma Campus, Henties Bay, Namibia

Misheck Musokwa The Southern African Confederation of Agricultural Unions, Lyttelton, Centurion, Pretoria, South Africa

Morleen Muteveri Department of Mathematics, Statistics and Computer Sciences, School of Natural Sciences, Great Zimbabwe University, Masvingo, Zimbabwe

Adornis D. Nciizah ARC—Natural Resources & Engineering, Irene, Pretoria, South Africa

Busi Ndaba Agricultural Research Council—Natural Resources and Engineering, Pretoria, South Africa

Neo Edwin Nyakane Agricultural Research Council—Vegetable, Industrial and Medicinal Plants, Irene, Pretoria, South Africa

Patrick Nyambo Risk and Vulnerability Science Centre, University of Fort Hare, Alice, South Africa

Isaac Nyambiya Department of Mathematics, Statistics and Computer Sciences, School of Natural Sciences, Great Zimbabwe University, Masvingo, Zimbabwe

Linda U. Obi Godfrey Okoye University, Enugu, Enugu State, Nigeria
Agricultural Research Council—Natural Resources and Engineering, Pretoria,
South Africa

Frances N. Olisaka Godfrey Okoye University, Enugu, Enugu State, Nigeria
Benson Idahosa University, Benin City, Edo State, Nigeria

Cosmas Parwada Tugwi Mukosi Multidisciplinary Research Institute (TMMRI),
Midlands State University, Zvishavane, Zimbabwe

H. T. Pule Agricultural Research Council—Animal Production, Irene, Pretoria,
South Africa

Ashira Roopnarain Microbiology and Environmental Biotechnology Research
Group, Agricultural Research Council—Natural Resources and Engineering,
Pretoria, South Africa

Department of Environmental Sciences, College of Agriculture and Environmental
Sciences, University of South Africa—Florida Campus, Florida, South Africa

Batizi Serote Agricultural Research Council—Vegetable, Industrial and Medicinal
Plants, Irene, Pretoria, South Africa

Mariette Truter Agricultural Research Council—Vegetable, Industrial and
Medicinal Plants, Irene, Pretoria, South Africa

Isaiah I. C. Wakindiki KCA University, Nairobi, Kenya

Collin L. Yobe University of South Africa, Graduate School of Business
Leadership, Midrand, South Africa

Part I

Uses of Marginal Lands

Utilization and Improvement of Marginal Soils Through Large Stock Grazing in Semi-Arid Summer Rainfall Areas in South Africa



M. V. Kidson, S. M. Grobler, and H. T. Pule

1 Introduction

With the world population expected to grow from 8 billion to a projected 10 billion by 2050, the significance of natural arid and semi-arid rangelands becomes increasingly crucial (Alkemade et al. 2013). Currently, these ecosystems cover approximately 25% of the Earth's land surface, supporting over one billion people's livelihoods through livestock grazing and agriculture (van Oudenhoven et al. 2015). In Africa alone, rangelands account for approximately 65% of the total land surface (Nalule 2010), and provide a variety of ecological, cultural, biological, and socio-economical goods and services (Mussa et al. 2016). However, rangeland degradation poses a serious threat globally, including in sub-Saharan Africa impeding the effective management of arid and semi-arid areas (Mureithi et al. 2014). Approximately 75% of the world's grazing land has already lost its capacity to sustain livestock (Moyo et al. 2013) due to local and global drivers of degradation. South Africa has been particularly impacted, with approximately 70% of its land surface degraded caused by soil erosion resulting in poor soil fertility and productivity (Le Roux et al. 2007). Notably, the grasslands and savannas have experienced substantial loss of soil organic carbon (SOC) compared to croplands and areas with a mix of natural vegetation and crops within regions like Argentina, southern Africa, and Australia. The restoration and conservation of these rangelands are of utmost importance to ensure the continued provision of essential services and support for both ecosystems and the communities that depend on them in the face of future population growth.

M. V. Kidson (✉)

ARC – Natural Resources and Engineering, Pretoria, South Africa

e-mail: Michael@arc.agric.za

S. M. Grobler · H. T. Pule

ARC – Animal Production, Irene, Pretoria, South Africa

However, South Africa is a country of extreme contrasts, with 80% of the country defined as arid to semi-arid, with an average rainfall of 450 mm per annum, compared to a world average of 910 mm per annum (Alkemade et al. 2013). The South African National Report on Land Degradation (NRLD; Wessels et al. 2007) indicates that rangeland degradation is severe on communal lands and small patches of commercial lands. Although rangeland productivity and resilience to environmental variability are a function of soil health and microbial functional diversity (Plassart et al. 2008), the effects of rangeland management and land-use change on land degradation and agricultural productivity remain poorly understood (UN 2011). This is because most soil functions recover slower than the biotic attributes such as vegetation structure and diversity, and consequently, they are only rarely measured (Ruiz-Jaen and Aide 2005). However, agro ecosystems that include grazing are more productive, stable and resilient when the soil is fully functional biologically, and they provide greater earnings and more abundant ecosystem services (Teague et al. 2013). Monitoring the impacts of grazing management practices on soil quality (SQ) is essential to ensuring the sustainability of grazing systems (Amorim et al. 2020).

An appropriate grazing management practice is proposed as the best restoration strategy for overgrazed and degraded rangelands with poor vegetation cover and soil quality (Woodfine et al. 2009) because it enhances the vitality of mature perennial grasses. The long-term success or failure of all grazing strategies is centred on management's ability to control the frequency and severity of defoliation of individual plants over time and space (Heitschmidt and Walker 1996). Vegetation restoration and plant productivity appeared to be the major driver of improved soil quality on abandoned croplands (Raiesi and Salek-Gilani 2020). Soil quality can be defined as the capacity of a soil to function within an ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran and Parkin 1994). There are many approaches to rangeland restoration, but the most suitable approach can be determined by considering soil type, climatic conditions, the causes, and degree of deterioration, especially the degree of degradation (Van der Merwe and Kellner 1999). Clearly, how well grassland and savanna ecosystems are managed to regenerate soil and ecosystem function governs our future (Teague and Kreuter 2020). This chapter, aims to shed light on best grazing management practices that balances and sustains both soil, and plant health to achieve optimum ecosystem services and functioning.

2 Marginal Soils

Marginal soils are regarded as soils that are not suited to crop production due to one or more natural limitations, such as low rainfall, soil depth and/or erodibility potential. To understand the soils potential or limitation the formation of the soils will be considered, followed by natural limitations to the utilization of the soil.

2.1 Soil Formation

An understanding of soil formation is required to make sense of the veld, and its potential, so a brief tour of soil formation will be taken. Soil formation is dictated by five soil forming factors namely: parent material, climate, topography, living organisms and time. The parent material is the rock that is weathered to form the soil. The rock characteristics determine the soil characteristics. Granite is a volcanic rock that has a high percentage of coarse silica and low number of basic ions. This results in an acidic soil with a high percentage of coarse sand. The soils are deep red and well suited to cultivation, having a low erodibility (Kidson 2014), however due to the acidic nature of the soil and low calcium and magnesium content, they are of a low fertility. If lime is applied the soils can be high yielding. Similarly, the veld is a sour veld, which is palatable in summer, but has low palatability and nutritional value in winter. These soils occur in the eastern part of Mpumalanga (Jansen van Jansen 2002).

Dolerite is a rock with a high percentage of basic ions, thus forming a loam fertile soil with a neutral pH. The veld is of a nutritional value in summer and winter. Sandstone when weathered forms sandy soils, of a low fertility, and is prone to erosion by the wind, as seen in the Free State province. Due to the low fertility, and leaching of basic ions, the soils are acidic in nature, with a resultant sour veld (Laker 2021).

Climate is the long-term average temperature and rainfall for a district. A hot dry climate will result in soil that has a low state of development as in the Karoo. The rainfall is around 400 mm per annum while the evapotranspiration is 1500 mm, resulting in little water for chemical reactions and poor or little development. As opposed to the high rainfall and hot climate of the eastern Mpumalanga, the soils are highly developed with a lower chance of erosion.

Topography is the arrangement of the physical natural features, such as hills, slopes, valley bottoms and flat land. Typically, the soils on the top of hills are shallow and becoming deeper when moving down the slope. With the deepest soils in the valley bottom due to the natural erosion or movement of the soils from the hill slopes to the valleys. A secondary feature following the topography is soil water. The soils on the top of a hill are generally shallow due to low water content and erosion of the soil. Little water accumulates, with most running down the slope through the horizon, and accumulating in the valley bottom. The topsoil's on the crest are shallow and low in fertility with the resultant pasture of a low nutritional value and carrying capacity. The soils on a slope in a high temperature and rainfall area, such as Mpumalanga, are less vulnerable to erosion and high in nutrition, due to the soils being more highly developed (Laker 2021). Valley bottom soils often have a gleyed horizon (water accumulating in the horizon through the year each year) or soils that form with a structure B-horizon. This soil is highly vulnerable to erosion, and structured horizon is an impediment to root growth, water movement and deep cultivation. The topsoils are prone to crusting and are highly erodible. The structured soils are the result of the movement of the clays that swell and shrink when wetted and

dried, from the A-horizon (Fey 2015). Further understanding can be obtained from Fey (2015), Laker (2021), and Huang et al. (2012).

Living organisms such as lichen on rocks have hyphae that penetrate the rock and release enzymes that dissolve the nutrients as a source of nourishment to the blue-green algae, playing a large role in aiding soil formation. Further, the organisms in the soil decompose plant material, releasing organic acids, which aid in soil formation processes. The amount of organic material in the soil is one of the determinants of soil health. Organic material has a number of benefits including slow release of plant nutrients, a more stable soil structure, improved water infiltration, and a nutrient source for microbes. Plants give off exudates, which includes sugars, which microbes use as an energy source. They also spend energy converting some of the sugars into more complex structures, which helps bind soil particles for an improved soil structure. An improved soil structure ensures improved water infiltration, with a greater chance of the plant's survival. Soil formation is a slow process. The time taken to form 10 mm of topsoil is 100 to 200 years, which means if lost it is lost in our lifetime.

South African soils have been classified using a practical system that has evolved over several years. The classification system gives a good practical description of the soils with the resultant possible uses of the soils. In 2018 the most recent revised soil classification book (Soil Classification Working group 2018) was published, where the anthropogenic influences, such as mining, are also considered.

From the description there are many factors that would lead to a soil being classified as marginal. Soil depth is of importance because the plant roots need to be able to have as large a quantity of soil reserve water available to carry the plant from one rain event to another. The soil is shallow overlying rock or stones. Nevertheless, grasses can thrive in such environments by extending their roots into rock fissures to access water reservoirs (Laker 2021).

Below outlines an example of where soil characteristic makes an area that would be described as unsuitable or marginal, suited to crop production. Farmers in the eastern Free State struggle with two distinct challenges related to rainfall. First, the region experiences relatively low annual rainfall, averaging around 400 mm (ARC-ISCW 2004). Second, rainfall typically arrives in the form of thundershowers. Given that the topsoil is predominantly sandy, a significant portion, if not all, of the rainfall readily infiltrates into the soil, eventually accumulating on the impermeable layer. Consequently, this phenomenon ensures that the entirety of the precipitation becomes available for the crops.

Soil erosion is a natural process that takes place on earth. However, the rate at which it is taking place at present is unsustainable. Soil erosion in South Africa is extensive with an estimated soil loss of 13 tons of topsoil/ha/year. This is most certainly unsustainable as the rate of soil formation is about 5 ton/ha/year (Le Roux 2014). Certain soils are more prone to soil erosion, such as the duplex soils and the windblown soils in the Free State province. Topsoil is crucial as 80% of the feeder roots occur in this horizon, which is most fertile. Moreover, seed germination is most successful in the top soil. In an effort to boost crop cultivation and simplify the recommendations, in the Transkei, a blanket rule was put into place that

recommended that a slope of 12% or less could be cultivated. In certain areas large scale erosion took place. D'Huyvetter (1985) found that each soil needs to be considered separately as erodibility varies between soil types. Furthermore, he found that with increasing rainfall there was a decrease in soil erosion. Further demonstrating that the higher the rainfall and temperature, the more developed is the soil.

2.2 Soil Degradation

Soil erosion is the single biggest environmental problem with wide ranging social and economic problems (Stern 1990). The result is the topsoil is eroded, resulting in low soil fertility, poor water infiltration and pioneer weeds and grasses growing, with a low carrying capacity. Researchers, including Dave Johnson at New Mexico University (Johnson 2016), have achieved very good results on rehabilitation of degraded soils, by the introduction of livestock in a strictly managed grazing system. The soils can be further built up by inoculation with indigenous microorganisms. The inoculum is made by making a quality compost that is well aerated, such as with the Johnson-Su bioreactor (Johnson 2021). Following Dave's method of making the compost, the resultant compost is rich with bacteria and fungi, added to water and spread over the soil. The most economical way of distributing the microorganisms is by mixing the compost in water and spraying on the soil.

The soil is a living organism with more microbes in a teaspoon of healthy soil than people on the earth, with incredible diversity that are paramount in the biogeochemical cycling of both organic and inorganic nutrients. With the diversity we have named only about 1% of the microbiota. This is largely due to a small number of organisms that can be cultured in the laboratory. With the latest technology, we are starting to open the window on the soil micro fauna and flora (Ramirez et al. 2014). This with the objective of understanding the diversity and functioning, before microbial technologies are applied (Bolton et al. 1992). The largest influence on the plant and microbial community is the rhizosphere, which is the volume of soil adjacent to the root, and the rhizoplane, i.e. the soil attached to the surface of the root. Soil contains a vast diversity of microbes; however, the primary determinant of microbial composition is the soils geochemical composition, followed by plant community (Garbeva et al. 2004).

Arbuscular mycorrhizal fungi (AMF) perform a wide variety of functions in the soil and have considerable influence on the maintenance of soil health (Jeffries et al. 2003). AMF secrete a water stable protein, glomalin, which is deposited on the outer surface of the hyphae. This in turn helps form water stable soil aggregates, which helps stabilise the soil, improving water infiltration and reducing soil erosion (Miller and Jastrow 2000). The energy used by AMF to stabilise and improve the soil quality is an investment by the fungi ensuring the plants health and survival. All geochemical cycles are governed by the soil, and more specifically the microbiome (Yaseen et al. 2012). Further, due to the very long hyphae of the fungi, they occupy very large volume of the soil. The hyphae can be 3 to 20 metres per one gram of soil

and it supports plant health by supplying water and nutrients and protecting the plant from potential disease-causing organisms (Singh et al. 2004).

In no-till and conservation agriculture (CA) soil it has been found that there is a higher concentration of Ca, P and Mg. This can be attributed to the influence of fungi releasing the plant nutrients and reduced leaching, due to a higher soil carbon content and soil structure (Mbuthia et al. 2015). This would be beneficial for the pasture as no fertilizer would be required and healthier livestock will be reared.

A group of microbes referred to as plant growth promoting microbes (PGPMs) supply various benefits to the plant including regulation of hormone and nutritional balances and plant growth regulators produced to resist phytopathogens (Spence and Bais 2015). They are able to fix atmospheric nitrogen, solubilise phosphorous and produce plant hormones (Ahmad et al. 2011). Other mechanisms include nutrient mobilization, production of exopolysaccharides and rhizobitoxine that helps the plant cope in the unfavourable environment (Vardharajula et al. 2011).

Increasing numbers of farmers are adopting CA as a crop production system, and finding that less fertilizers, herbicides and insecticides are required as the micro-biome develops to healthy populations and diversity. Similarly in the veld, the micro-biome can be developed with grazing strategies to help build the soil to a healthy state. South African soils are low in Phosphorous, but this can be alleviated with a healthy AMF population (Smith and Read 1997).

3 Background to Grazing on Natural Veld

It is a well-known fact that natural rangeland is one of the main feed sources of ruminant animals in South Africa (Meaker et al. 1980). This is also true for the South African beef industry, which forms the biggest component of the large stock ruminant component. When looking at the traditional beef producing areas, the soils are usually marginal with limited agricultural potential due to unpredictable rainfall, high ambient temperatures, shallow soils with low soil fertility (Meaker 1984).

Due to the development and improvement of agricultural production technologies worldwide, crop production has increased vastly since the 1950s. Unfortunately, the volatility of the current world markets and high prices of raw material, makes it difficult for intensive livestock producers to remain profitable. Although the cost of providing fodder to the grazing herd is more complex to quantify, it remains an important input (Foster et al. 2014) and according to Pogue et al. (1996) grazed forage is approximately a third of the cost of preserving forage, based on total digestible nutrients per kilogram of product. Against this background, the production costs from natural rangeland are still the lowest (Van Pletzen 2009). Extensive beef production on these marginal soils is therefore a practical method of turning this low-cost fibre-rich feed source into high-quality protein sources for human consumption (Scholtz et al. 2013; Van Pletzen 2009).

The South African natural rangeland are also very diverse (Acocks 1988), with considerable differences in botanical composition, production potential and

nutritional value. These values also differ between different seasons and years due to the large variations in annual rainfall and rainfall distribution, as well as different soil types, which are subsequently reflected in the performance of the animals (Reid and Jung 1982; De Waal 1990).

Grazing ruminant production, is determined not only by changes in nutrient requirements, quantity and quality of the available rangeland but also by the climate and physical environment (Reid and Jung 1982). Although the plant and animal component are usually investigated separately, extensive beef cattle production cannot be studied independent from the rangeland on which it is kept—especially because of the dynamic balance between the vegetation and grazing animal consuming it.

Various past studies focused on cow-calf productivity of large frame animals in different pasture systems (Gregory et al. 1978; Oliver 1978; Knox et al. 1982); adding legumes in grazing systems (Hoveland et al. 1978; Stricker et al. 1979; Morrow et al. 1988); and by making use of different calving seasons (Bagley et al. 1987; Gaertner et al. 1992). Although these tools play an important part of cattle production, the effects of cattle and rangeland productivity must be evaluated in the specific climate, the type of rangeland, the soil depth, condition and soil type, as well as the breed of animals.

3.1 Effect of Grazing on the Grass Plant

As summarized by Torrano and Valderrábano (2004) the most important effect of grazing on vegetation is the reduction of the photosynthetic capacity due to the reduction of leaf area. This reduces the supply of assimilated compounds to roots, seeds, and development of new shoots (Willard and McKell 1978; Donaghy and Fulkerson 1997). Therefore, the success of grass plants grazed by animal, will depend for the most part on the efficacy of the plants morphological and physiological adaptations for growing new leaves to replace the consumed biomass (Roundy and Ruyle 1989; Herms and Mattson 1992; Edenius et al. 1995).

A model developed by Whitham et al. (1991) is used to evaluate and analyse compensation mechanisms of the grass plant to grazing. The model considers the plant to be a balanced system of sources and sinks. The source organs is described as the parts specialised in the net gain of carbon (photosynthetic and storage organs), whereas the sink regions are specialising in growth and reproduction (growing meristems and flowers). According to this model, plants can physiologically compensate for the damage caused by grazing by making use of a response of either the sink or source organs. The source organs not being damaged by grazing, could respond by supplying increased amounts of photo-assimilated compounds to the sink organs. This process occurs by the increase of photosynthetic efficiency (compensatory photosynthesis) as a result of the elimination of older, less active tissue and increased amounts of light reaching the lower tissues, or due to the increased efficiency of water use due to the decrease in transpiring surfaces (McNaughton 1979; Nowak

and Caldwell 1984). The plant's response to grazing by the sink organs usually consist of an increase in the number of growing points (Whitham et al. 1991). This is usually caused by the removal of the dominant apical meristem leading to the growth stimulation of the lateral buds (Briske 1991).

There is an ongoing debate between those who advocate that grazing is bad for plants (Belsky 1986) and those who suggest that grazing is beneficial to the plants through biological success and increased productivity (Paige and Whitham 1987) due to the morphological and physiological adaptation of the plants. It is also noteworthy that the apical and intercalary meristems in herbaceous monocotyledonous plants are less vulnerable to grazing by large ruminants due to their basal location. However, the sprouting shoots of herbaceous dicots' are found in terminal or lateral positions, increasing the likelihood of damage by grazing animals (Briske 1991). The lack of grass plants in certain parts of the world has been linked successfully to the absence of grazing animals. This is mainly due to grass plants being well adapted to the physical environment that grazing animals produce (Torrano and Valderrábano 2004).

In a study by Manley et al. (1997), they compared continuous or season-long, 4-pasture delayed rotation, and 8-paddock time-controlled rotation grazing on mixed-grass rangeland under light, moderate and heavy stocking rates near Cheyenne, Wyoming from 1982 through 1994. Results from this study indicated that stocking rate and grazing strategy had no effect on above-ground biomass and little effect on below-ground biomass. Under heavy stocking, forbs increased and therefore the forbs contributed to the above-ground biomass, especially under time-controlled rotation grazing. Otherwise, effects of grazing strategy, level vs. slope, and north vs. south slope on vegetation were insignificant (Manley et al. 1997).

Other previous studies indicated that the vegetation composition of mixed-grass rangelands, as well as the performance of grazing cattle is influenced by both stocking rates and grazing pressure in Canada (Dormaer et al. 1994), North Dakota (Rauzi 1963; Brand and Goetz 1986) as well as Montana (Reed and Peterson 1961; Houston and Woodward 1966). However, almost no change in vegetation composition has been observed in a 4-year grazing trial in Montana (Vogel and Van Dyne 1966), North Dakota (Hofmann and Ries 1989) and in the Sourish mixed bushveld of South Africa (Grobler 2016). These short-term studies clearly illustrate the need for long term studies over many years and climate cycles to measure the impact of grazing in different locations. The biomass availability and rangeland quality are also greatly influenced by differences in annual rainfall and rainfall distribution leading to differences in botanical composition and appropriate stocking rates over time (Fourie 1983; De Waal et al. 1989).

3.2 Veld Management: Definitions and Implications

The section below provides definitions of key terms that will be used throughout this chapter:

3.2.1 Carrying Capacity

Carrying capacity is defined as the area of land required to maintain a specific animal unit (large stock unit, small stock unit etc.) through utilization of the vegetation in order to achieve maximum profit in the short term—while maintaining the condition of the vegetation and soil in such a way as to be able to fulfil the needs and aspirations of future land users (Van Oudtshoorn 1991).

3.2.2 Grazing Capacity

Grazing capacity is often loosely used to describe the productivity of all vegetation on a farming unit. This is not correct because the term ‘grazing’ specifically refers to the utilization of grass by animals. In practical terms, the difference between grazing capacity of the rangeland and stocking rate is that grazing capacity refers to the true number of animals that the vegetation can sustain and the stocking rate to the number of animals the manager perceived that the vegetation could sustain (Smit 2009).

3.2.3 Stocking Rate

Stocking rate is generally defined as the area of land in a management system allocated to each animal unit. Stocking rate is therefore an expression of the number of animals that are run on his veld.

3.2.4 Browsing Capacity

Browsing capacity relates to the woody component of the vegetation (Aucamp and Barnard 1980) to be consumed at limited heights by different animal species. The carrying capacity of veld, where woody vegetation occurs, is the sum of its browsing capacity and its grazing capacity.

3.3 Practical Implications of Stocking Rate and Carrying Capacity

In extensive beef production, stocking rate has the greatest influence on cattle production, the long-term condition of the rangeland and ultimately profitability (Booyesen 1975). It must be noted that ultimately, stocking rate is more important than other factors related to grazing management and the number of camps on a

farm. A correctly stocked four-camp system is far more desirable than an overstocked multi-camp system (Danckwerts and Drewes 1989).

For extensive beef cattle producers to be successful in the long run, the following components related to stocking rate must be taken into account: (a) financial requirements and ability to source or produce additional feed, (b) the biological requirements of the rangeland, (c) the biological requirements of the soil and (d) the biological requirements of the animals. If all these factors are not taken into account, the system will ultimately fail (Danckwerts and Teague 1989).

Although most producers realize that overgrazing leads to rangeland deterioration, there is always the temptation to increase animal numbers to strengthen potential income. However, if stocking rates are applied more than the carrying capacity, the action may be counterproductive. In the long term, overstocking will lead to deterioration of the rangeland, resulting in lower animal productivity and therefore decreased financial return (Danckwerts and Teague 1989).

When studying the relationship between animal production per animal unit and the stocking rate of the rangeland, it is clear that animal production per animal unit head will remain constant at very light stocking rates, after which it drops as the stocking rate increases. In contrast, total animal production per hectare increases with increasing stocking rate up to a critical stocking rate, after which it drops rapidly (Jones and Sandland 1974).

The carrying capacity of a specific rangeland must therefore always be between the two stocking rates where maximum production per hectare and maximum production per head occur. When functioning at the critical stocking rate, any increase in stocking rate will result in lower animal production and saleable animal products, resulting in decreased financial returns (Danckwerts and Teague 1989).

3.4 Grazing Strategies

Different grazing strategies in different climatic zones have evolved over time from the need to sustain the efficient use of the rangeland (Manley et al. 1997) as well as livestock performance (Grobler et al. 2013). However, rangeland management practices may cause either deterioration of the rangeland or improve it (Van Pletzen 2009). Commonly used grazing strategies include continuous grazing, rotational grazing, strip grazing and multi-species grazing (Ball et al. 2007). These strategies are applied in different ways by either increasing or decreasing the frequency and intensity of defoliation within a specific time. Grazing strategies are summarised in Table 1.

Table 1 Grazing strategies

Grazing strategy	Aim	Objectives
1. Continuous grazing	Animals having uninterrupted and unrestricted access to a specific area throughout the year (Ball et al. 2007).	Yearlong pasture utilisation
2. Rotational grazing	Successive grazing of these enclosures in rotation is thus involved so that not all the veld is grazed simultaneously (Trollope et al. 1990).	1. Control the frequency at which the plants are grazed 2. To control the intensity at which the plants are grazed. 3. To reduce the extent to which the veld is selectively grazed
3. Strip grazing	Strip grazing is the use of a movable electric fence to allot enough forage to a group of animals for a relative short period of time whereafter the fence is moved towards the next grazing area (Ball et al. 2007).	High utilization or high intensity grazing is usually performed by making use of some form of strip grazing.
4. Multi-species grazing	The use of different livestock species with different grazing and browsing habits and needs i.e., cattle, sheep or goats and may even include wildlife (Ball et al. 2007).	A more complete specie utilisation
5. High intensity grazing	To mimic the way grasslands are utilized by grazers in a natural situation	Intensive management of grazing while preventing over grazing.

3.5 *Effect of Livestock Grazing on Physical and Chemical Properties of the Soil*

Livestock play a very important role in improving or having a detrimental effect on marginal land. One large livestock unit can provide between 9 and 17 ton of manure per year, which is an important source of organic matter for the soil (Sukmana et al. 1994; Köhler-Rollefson 2015). In a study conducted by Modernel et al. (2013), it was demonstrated that soil erosion rates tend to rise as cropping activities constitute a larger portion of the land needed to produce 1 kg of body mass, especially in cases where livestock production necessitates supplemental feed. Nevertheless, when cultivating on marginal soils, the primary objective should consistently revolve around enhancing livestock production and income, while minimizing soil erosion and actively promoting soil conservation (Sukmana et al. 1994; Köhler-Rollefson 2015).

In general, grazing livestock impact the rangeland and soil through three processes: plant defoliation due to the grazing of animals, trampling of the soil and deposition of both urine and faeces onto the soil. Although the effects of these processes cannot be separated, their impact and direction on the soil vary independently from each other as they are diversely influenced by soil texture (Valentin 1985; Hagwet et al. 2014), soil moisture content (Proffitt et al. 1995; Hatfield et al. 2005), herbage physiological state (Hiernaux and Turner 1996), stocking rate,

grazing frequency, animal species involved, and type of herd management (Hiernaux et al. 1999; Liniger and Mekdaschi Studer 2019). Each of these processes have short-term effects on vegetation and soils and have long-term effects over time on both the species composition of the vegetation and the ability of the soil to support plant production.

4 Improving the Quality of the Soil and Veld through Grazing Techniques

The South African National Report on Land Degradation (NRLD; Wessels et al. 2007) indicates that rangeland degradation is severe on communal lands and small patches of commercial lands. While rangeland productivity and its ability to withstand environmental fluctuations are influenced by soil health and microbial functional diversity (Plassart et al. 2008), there is little understanding of the impact of rangeland management and land-use changes on land degradation and agricultural productivity remains limited (UN 2011). This is because most soil functions recover much more slowly than the biotic attributes such as vegetation structure and diversity, and consequently, they are only rarely measured (Ruiz-Jaen and Aide 2005). However, agro ecosystems that include grazing are more productive, stable and resilient when the soil is fully functional biologically, and they provide greater earnings and more abundant ecosystem services (Teague et al. 2013). Monitoring the impacts of grazing management practices on soil quality (SQ) is essential to ensure the sustainability of grazing systems (Amorim et al. 2020).

An appropriate grazing management practice is proposed as the best restoration strategy for overgrazed and degraded rangelands with poor vegetation cover and soil quality (Woodfine et al. 2009) because it enhances the vitality of mature perennial grasses. The long-term success or failure of all grazing strategies is centred on management's ability to control the frequency and severity of defoliation of individual plants over time and space (Heitschmidt and Walker 1996). Vegetation restoration and plant productivity is the major driver of improved soil quality on abandoned croplands (Raiesi and Salek-Gilani 2020). Soil quality can be defined as the capacity of a soil to function within an ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran and Parkin 1994). There are many approaches to rangeland restoration, but the most suitable approach can be determined by considering soil type, climatic conditions, the causes and degree of deterioration, especially the degree of degradation (Van der Merwe and Kellner 1999). Clearly, how well grassland and savanna ecosystems are managed to regenerate soil and ecosystem function governs our future (Teague and Kreuter 2020).

4.1 Grazing Management to Restore Soils and Plant Health

Ruminants including domestic livestock, have been blamed for causing environment problems and harming human well-being. However, with appropriate management, these animals can play a significant role in reversing environmental damages caused by human mismanagement and neglect (Teague and Kreuter 2020). For long-term sustainability of rangelands, livestock producers need to adopt grazing management practices that improve soil and ecosystem function and resilience (Havstad et al. 2007). The principles of high-density grazing under certain climatic conditions with an average rainfall of at least 250 mm per year (Gabe Brown 2013), have gained recognition in regenerative agriculture (Teague and Barnes 2017). Various names are used to refer to the set of management practices associated with high-density grazing such as holistic grazing, adaptive multi-paddock grazing, mob grazing, short-duration grazing, and/or cell grazing. High-density grazing, like adaptive multi-paddock grazing is a form of rangeland management aiming to strategically mimic the ways grasslands are supposedly utilized by grazers in a natural situation (Hoffman 2003; Savory and Butterfield 2016). It involves periodic concentration of grazing animals with subsequent extended post-defoliation recovery periods, which lead to net ecosystem benefits such as increased soil carbon, nutrient cycling, soil microbial function, above and below ground biodiversity, surface water infiltration, rooting depth, plant cover, herbaceous biomass, and ultimately ranch profitability (Jakoby et al. 2015). With high density or adaptive multi-paddock grazing, it is not intensive grazing but intensive management of grazing as it reverses the impacts of intensive grazing by specifically avoiding overstocking of and overgrazing by livestock in an adaptive manner in response to variable weather (Wang et al. 2018a, b).

High-density grazing (also known as multi-paddock grazing) has the potential to reverse the causal mechanisms of ecosystem degradation that occur under continuous grazing. This is done by decreasing bare ground, increasing water infiltration rates and soil water storage capacity, reducing surface water runoff and soil and nutrient losses, increasing the ratio of fungi to bacteria in the soil, increasing soil carbon, and ultimately restoring productive herbaceous plant communities by reducing the ability of herbivores to select only the most nutritious grass species (Teague et al. 2013). Ecosystem services that are enhanced using this grazing system include soil stabilization and formation, water infiltration, carbon sequestration, nutrient cycling and availability, biodiversity, and wildlife habitat, which cumulatively result in increased ecosystem and economic stability and resilience. Generally, farmers who apply regenerative high-density grazing management practices to restore ecosystem functionality create sustainable, resilient agroecosystems cost-effectively (Teague and Kreuter 2020).

4.2 *Alternative Management Approaches to Restore Soil and Plant Health*

Agricultural abandonment is a management option to restore surface cover and maintain or even enhance SOM storage, nutrient cycling, and soil productivity in degraded rangelands (Novara et al. 2017). In contrast, when rangelands are converted to croplands, harvest of aboveground biomass and soil disturbance by intensive tillage practices reduce surface cover and destabilize the topsoil, leading to loss of soil organic matter (SOM) and structural stability (Ding et al. 2013). While other soil nutrient parameters (soil organic carbon, total nitrogen content and C/N ratios) remained unchanged, some (Phosphorus and Potassium content) are significantly decreased with grazing (Raiesi and Asadi 2006). The net grassland-cropland conversion increased annual soil erosion by 7.9%, nitrogen (N) loss by 3.7%, and soil organic carbon loss by 5.6% relative to that of existing cropland, despite an associated increase in cropland area of only 2.5% (Zhang et al. 2021).

In severely degraded semi-arid rangeland, withdrawal of livestock grazing is often not sufficient to initiate the autogenic recovery of vegetation (Opiyo et al. 2011), and probably soil health. Maussa et al. (2009), contend that the short-term livestock removal does not lead to a significant improvement of soil health. Grazing enclosure is one of the widely employed interventions to rehabilitate degraded lands, restock biodiversity and restore soil fertility (Mekuria et al. 2011). The soil organic carbon and nitrogen content in grazing enclosures is higher than on grazed areas (Damene et al. 2020).

5 A Case Study for High Intensity Grazing in Eastern Free State

The farm is located near Reitz, in the Free State of South Africa occurs on the Karroo system, with the Geological Beaufort series (Hatch and Corstorphine 2022). The sandstones are fine or medium grained through the entire region, and the resultant soil is sandy, with carbon having a residence time of 45 years (Carbon dating). The farm is in its fourth generation, having been established in 1923. Danie Slabbert and his family currently farm maize, soybeans, wheat, sunflowers, and cattle. However, the previous farming practices were destructive to the soil and the environment, as they involved killing natural predators. Each year in August, the air becomes saturated with fine topsoil particles carried by the wind, to the extent that railway lines become obstructed by this topsoil, leading to the interruption of train services. Despite this recurring issue, farmers have continued to employ traditional cultivation methods that result in the lack of vegetation cover, leaving the topsoil vulnerable to erosion (Farmers Weekly 2019).

After forming a study group, the farmers naturally progressed to Conservation Agriculture (CA) as an improved farming production system, which he initiated

13 years ago. At a workshop hosted at the University of the Free State, Hendrik Smith, a recognized expert in Conservation Agriculture (CA) showed farmers a comprehensive seven-step approach (see Fig. 1, Keesstra et al. 2019) towards embracing regenerative agriculture (Smith 2019). These steps entail transitioning from conventional cultivation methods to no-till practices and gradually reducing input usage, ultimately leading to regenerative agriculture with minimal to no external inputs. However, shifting to CA requires a change in mindset from viewing bare soil as productive to viewing soil covered in organic matter as more productive, with associated benefits.

An example of the benefit of reduced inputs, is the fact that during the 2020 season the farmer, reduced the nitrogen application by half, for his potato crop. The result was a longer shelf life for the produce. The yields are comparable to his neighbours during normal years, but during drier years (important in the context of possible future climate change), the yields outperformed his neighbours. He reduced the maize and soya bean plant row width from 50 to 30 cm with the objective of maximising on soil water utilisation and shading of the soil to reduce weed competition.

The farm was also overgrazed, as indicated by the high population of undesirable grass species, such as two-coloured love grass (*Eragrostis bicolor*), broad leaved turpentine grass (*Cymbopogon excavates*), cat’s-tail three-awned grass (*Aristida congesta*) and South African lovegrass (*Eragrostis plana*).

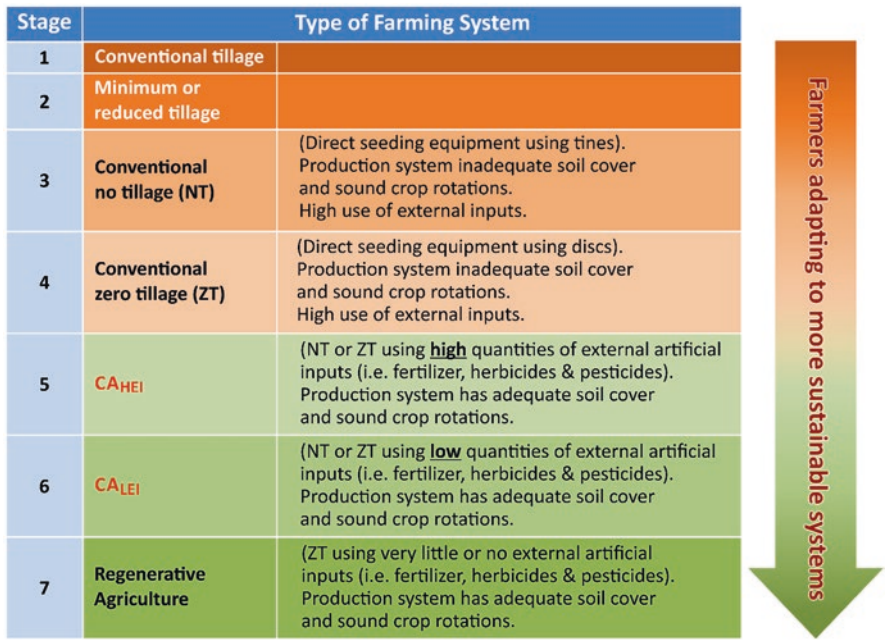


Fig. 1 The steps to the adoption of regenerative agriculture (Smith 2019)

Danie Slabbert has been practicing ultra-high density grazing for the past 5 years to simulate the natural grazing effect of herds of livestock bunching together to defend themselves from predators. This is done by grazing 500 Drakensberger cattle on 100-meter-wide strips, moving the herd 10 m at a time for 1 h (Fig. 2). The grazed veld is then allowed to recover for a year. The beneficial effect of this method is that the veld is force-grazed, giving the beneficial grass species the opportunity to regrow. This outcompetes the detrimental grass species listed above, and forbs have germinated for the first time in 50 years. The topsoil is dark in colour due to the higher carbon content, and the plant cover is very dense, with no bare soil (Fig. 3).



Fig. 2 The veld has been grazed and the electric fence is ready to be moved for the next hour of grazing. Note the density of the grass cover with a high density of plant growth. (Photo by Michael Kidson)



Fig. 3 A slice of the topsoil horizon. Although the soil is sandy, it is dark coloured from the high organic material. Note the forbs in the soil sample (Photo by Michael Kidson)

The vegetation is so dense that it is difficult to open a space in the vegetation to place an auger to take a soil sample.

Dung heaps had accumulated after the cattle had moved to the next strip for grazing. Within 5 to 10 min, several different species of dung beetles had converged on the dung and started to disperse and bury it. This has the added benefit of placing the dung in the soil, as well as incorporating the cattle's gut microorganisms, which helps to inoculate the soil. Neighbouring farmers do not believe that dung beetles occur in their district (Van Rooyen 2013).

Another beneficial effect of the Regenerative Agriculture approach on the livestock is that the livestock do not require as much veterinary medication, due to the health of the soil, plants and ultimately the cattle. There is reduced assistance needed for calving, however it is dependent on the cattle breed vigour.

6 A Study on the Effects of Grazing on Sandy Soils in Dry Semi-Arid Rangelands in Sub-Saharan Africa

A four-year study conducted by Hiernaux et al. (1999) in Sadore, Niger looked at the effect of grazing by small stock on soil chemical properties, bulk density and soil surface features. Grazing treatments were a factorial arrangement of two stocking rates (62.5 and 125 kg live weight ha⁻¹) relating to four sheep:goat ratios (0:6, 2:4, 4:2 and 6:0 animals), with two paddocks per treatment and two control paddocks which were not grazed. Additionally, a natural fallow, which was previously subjected to 9 years of uncontrolled intense mixed grazing and an area protected from animal grazing for at least 15 years were also included in the study.

Soil samples were taken at depths of 0–2, 2–6, 6–14 and 14–30 cm below shrub canopy and soil bulk density was also measured in a subset of soil profiles. The soil was prone to crusting, thus the soil crusts and other soil surface features were assessed.

Over the four-year period, grazing had a substantial impact on the soil surface features, but there was no significant effect on the soil bulk density. There was a nonlinear relationship between soil properties related to the water infiltration index and grazing intensity. The soil water infiltration index increased at moderate stocking rates but decreased when stocking rate was higher.

There was a small decrease in N and P content and organic carbon were observed in the topsoil of the area which was heavily grazed over many years. However, these effects did not develop homogeneously over the study area or proportionately to the applied stocking rates or duration of grazing. Soils under shade as when sheltered by shrubs, had higher soil biological activity and organic carbon as well as greater N and P levels. These soils were however more affected by grazing than the soils with only herbaceous ground cover. The lag time associated with some of the feedback processes could explain the nonlinearity of other observed changes. This includes effects on soils due to changes in both vegetation composition and patterns over many years while adapting to grazing pressure (Hiernaux 1998).

Compaction of topsoil beneath the shrub canopy and vegetated patches were only observed in the treatments where intense grazing pressure was applied. Light grazing stimulated herbage production and grass growth whereas high grazing pressure promoted the growth of dicotyledons, and other unpalatable species.

The authors did mention that the extrapolation of the results of this trial to the Sahel region would also require a diversification of the study sites (land use, soil texture, topography), animal species and grazing system considered.

7 Conclusion

There are many different grazing strategies available, which can either benefit or deteriorate marginal soils and rangeland, depending on the management strategy adopted. Therefore, it is important to consider all the different factors impacting these soils e.g., type of animal grazing the land, carrying capacity of the land, soil type, annual rainfall and rainfall distribution, as well as the current status of the land before deciding which strategy will be most beneficial under specific conditions. There is no bad soil, just poor management of the soil, similarly for the veld. Although one of the biggest challenges facing farmers in South Africa is the limited rainfall, and high evapotranspiration rates, natural veld can be optimally utilised. Where the veld has been degraded, it can be rehabilitated with careful management. When planning a grazing strategy, the veld composition and carrying capacity needs to be considered and managed accordingly. In principle Conservation Agriculture can be adopted in most environments with low to high rainfall, however the fine tuning of the system will be required by determining the crop and cover crops chosen. A more holistic approach needs to be adopted and adapted for each farm.

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Optimizing Sweet Sorghum Production in Marginal Lands Through Conservation Agriculture: A Case Study from Eastern Cape, South Africa



M. E. Malobane, Adornis Dakarai Nciizah, and I. I. C. Wakindiki

1 Introduction

Sustainable production of biofuel as part of renewable clean energy is currently very important around the globe (Awogbemi et al. 2021; Malode et al. 2021; Yong and Wu 2022). Biofuel production assists in reducing the negative environmental impact associated with fossil fuels while supporting the current development and economy growth in many countries (Awogbemi et al. 2021; Khan et al. 2021; Al-Shetwi 2022). Production of biofuel will require crops that can generate high biomass even under marginal conditions (Mathur et al. 2017; Pancaldi and Trindade 2020). In South Africa, the former homelands are important in the production of biofuel feedstock (South African Department of Minerals and Energy 2007). However, the South African former homelands soils are fragile and degraded (Mani et al. 2021). This threatens the sustainable production of biofuel feedstock (Malobane et al. 2020) and the use of arable land, which is approximately 14% of the total agricultural land in South Africa is solely for food production (Malobane et al. 2018). In addition, the production of biofuel feedstock can only be done under rainfed due to water scarcity in the country (Mengistu et al. 2016). Thus, the production of biofuel

M. E. Malobane (✉)

University of South Africa, Department of Agriculture and Animal Health,
Florida, South Africa

e-mail: malobme@unisa.ac.za

A. D. Nciizah

University of South Africa, Department of Agriculture and Animal Health,
Florida, South Africa

Agricultural Research Council - Soil, Climate and Water, Pretoria, South Africa

I. I. C. Wakindiki

KCA University, Nairobi, Kenya

feedstock in South Africa will require crops which can do well under marginal soils and production systems that can enhance soil quality.

The use of lignocellulosic crops has been identified as the best option for sustainable biofuel production with low agronomic inputs (Velvizhi et al. 2022; Yong and Wu 2022). One of the potential leading lignocellulosic crops as biofuel feedstock is sweet sorghum (Mathur et al. 2017; Appiah-Nkansah et al. 2019; Dehghanzad et al. 2020). Sweet sorghum requires less agronomic inputs and can grow under marginal soils while not contributing to the food-fuel conflict (Malobane et al. 2018; Hossain et al. 2022). In addition, sweet sorghum provides high biomass and easily extractable high sugar content which are key to biofuel production (Kering et al. 2017; Mathur et al. 2017). Sweet sorghum can do better under pronounced marginal land conditions like drought, waterlogging and salinity compared to crops like maize (Almodares et al. 2011; Schittenhelm and Schroetter 2014). In addition, sweet sorghum has high water use efficiency and low agronomic requirements, thus, making it ideal for most smallholder conditions in South Africa (Mengistu et al. 2016; Malobane et al. 2018). The production of sweet sorghum is similar to that of maize (Zegada-Lizarazu and Monti 2012), which will make it easier to be produced by many farmers (Malobane et al. 2018). However, production of biofuel feedstock is done under intensive agriculture practices like the application of fertilizer and irrigation in order to achieve desirable biomass yield (Malobane et al. 2018). In addition, biofuel production is maximized by total removal of crop residues from the field (Dou et al. 2014). Both agricultural intensification and total removal of crop residues have negative impact on soil quality (Jat et al. 2019; Kopittke et al. 2019; Zhao et al. 2020; Mirzaei et al. 2021). Thus, the application of both practices has potential to worsen soil degradation in the former homeland soils.

The application of conservation agriculture (CA) was identified as a potential agricultural practice that can be implemented for the sustainable production of sweet sorghum as a biofuel feedstock in South Africa (Malobane et al. 2018). This is because CA enhance soil quality, reduce soil greenhouse gas emission, increase infiltration while reducing soil erosion (Lal 2015; Jayaraman et al. 2021; Jayaraman et al. 2022; Cárceles Rodríguez et al. 2022). CA also enhance crop yield mostly under rainfed conditions in semi-arid and arid regions (Sun et al. 2018; Sithole and Magwaza 2019; Mbanyele et al. 2022). The potential of CA as a sustainable production for sweet sorghum as a biofuel feedstock was mostly based on data from maize and sorghum research due to linked application under sweet sorghum. Therefore, local research on CA application under sweet sorghum is recommended (Malobane et al. 2018). Therefore, the overall objective of this chapter is to highlight the potential benefits of CA on soil chemical and physical properties as observed in some marginal lands of Eastern Cape Province in South Africa. This chapter presents recommendations for best practices for sustainable sweet sorghum production based on a study conducted in Eastern Cape, South Africa.

2 Characteristics of the Study Area

The field studies were conducted at the University of Fort Hare's experimental farm located at latitude 32°46'S and longitude 26°50'E. The region experiences a semi-arid, mild climate with an average annual rainfall of approximately 575 mm, concentrated from October to April. The predominant soil type is alluvial-origin Haplic Cambisol, known for its low fertility and hardsetting, unstable aggregates. Prior to the experiment, soil characteristics were measured: available phosphorus (P) at 71.87 mg kg⁻¹, cation exchange capacity (CEC) at 13.86 cmol (+) kg⁻¹, and total nitrogen (TN) at 460 mg kg⁻¹. Soil texture is classified as sandy clay loam.

The experiment by Malobane et al. (2020) investigated the effects of three factors - tillage, crop rotation, and residue management. The experimental design employed was a randomized complete block design with a 2 × 2 × 3 split-split-plot treatment structure replicated three times. The main plot was assigned to tillage, with two levels: no-tillage (NT) and conventional tillage (CT). The sub-plots were assigned to crop rotations, with two levels: sweet sorghum-grazing vetch-sweet sorghum (S-V-S) and sweet sorghum-fallow-sweet sorghum (S-F-S). Sub-sub-plots were assigned to crop residue retention at three levels: 0%, 15%, and 30% based on total harvested fresh biomass. Twelve treatment combinations were established under non-nutrient limiting conditions. The main plots were 12.8 m × 17 m, the sub-plots were 5.4 m × 17 m, and the sub-sub-plots were 5.4 m × 5 m in size. Figure 1 shows a portion of the trial layout.

Various soil physico-chemical parameters were measured using standard analytical methods. The soil pH and electrical conductivity (EC) were measured using an EC and pH electrode meter, respectively, in a soil:water ratio of 1:25, as described by Zhang et al. (2015). To determine the aggregate stability, the mean weight



Fig. 1 Trial layout of the sweet sorghum trial (Photo by Elvis Malobane)

diameter (MWD) was calculated using the fast-wetting method outlined by Le Bissonnais (1996). Soil aggregate binding agents such as the content of glomalin-related soil protein (GRSP) was analysed in accordance with the method described by Wright and Upadhyaya (1998) whilst SOC was determined using the Walkley Black method.

The mini disk infiltrometer was used to measure infiltration in the field. To ensure good contact between the soil and infiltrometer, a thin layer of silica sand was applied on top of the samples (Decagon Devices 2007). Measurements were taken every 30 s until at least 20 mL of water had infiltrated the disk infiltrometer reservoir (Decagon Devices 2007). The bulk density (BD) was determined from soil core samples that were not disturbed. For soil water characteristics, disturbed soil samples that passed through a 2 mm sieve were used. A water-permeable cloth was fixed at the bottom of each ring with soil and saturated with water from the bottom. Field water capacity (FC) and permanent wilting point (PWP) were measured at 33 kPa and 1500 kPa, respectively using pressure plates. The difference between FC and PWP, known as total available water (TAW), was calculated. A handheld penetrometer was used to measure penetrometer resistance, and three readings were taken at each plot.

The total nitrogen (TN) was measured using a dry combustion method (Carlo Erba NA 1500 Elemental Analyzer) whilst inorganic nitrogen, consisting of ammonium ($\text{NH}_4^+\text{-N}$) and nitrate ($\text{NO}_3^-\text{-N}$), was extracted using 1 M KCl and quantified using a colorimetric method with a continuous flow analyser (Mulvaney 1996). The total organic nitrogen (TON) was calculated by subtracting the inorganic nitrogen from the total nitrogen (TN). The P-Bray I method, as described by Kuo (1996), was used to determine the availability of P. The concentration of P in the extracts was then determined using a continuous flow analyser. The cation exchange capacity (CEC) and the presence of exchangeable bases—calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na)—were determined using the ammonium acetate method, as described by Sumner and Miller (1996).

3 Findings

3.1 Aggregate Stability SOC and GRSP

The effect of tillage, rotation and residue management are shown in Table 1. Tillage which was the main factor was the main treatment affecting aggregate stability and the selected aggregate binding agents (SOC and GRSP). In addition, GRSP was influenced by residue management. The application of NT increased MWD, SOC and GRSP compared to CT treatment (Malobane et al. 2021). CT application led to a reduction in MWD primarily by physically disrupting larger aggregates, which resulted in the formation of smaller micro-aggregates that are more prone to erosion (Zhang et al. 2012; Xiao et al. 2019). Under NT management, there was a 25% increase in MWD, a 13.83% increase in SOC, and a 20.23% increase in GRSP when compared to CT management (Malobane et al. 2021). The application of 30%

Table 1 Tillage, rotation and residue management effects on aggregate stability as measured by mean weight diameter (MWD) and selected binding agents (soil organic carbon (SOC) and glomalin-related soil proteins (GRSP))

	MWD	SOC	GRSP
Till.	0.005**	0.001**	0.001**
Rot	0.2869	0.8407	0.2367
Res. man.	0.6669	0.9285	0.037*
Till. × Rot.	0.2849	0.7428	0.7538
Till. × Res. man.	0.6193	0.9380	0.3219
Rot. × Res. man.	0.4397	0.8506	0.2490
Till. × Rot. × Res. man	0.9608	0.1528	0.7364

NB: Till: tillage, Rot.: Rotation, Res. man: Residue management, **: highly significant ($P < 0.01$), *: significant ($P < 0.05$). (Adapted from Malobane et al. 2021)

residue retention resulted in a 1.78% increase in GRSP compared to the treatment with 0% residue management (Malobane et al. 2021). The increase in residue management increased GRSP in this study (Malobane et al. 2021). The CT application increase mineralization of SOC leading to decline in SOC (Curaqueo et al. 2011; An et al. 2013), soil micro-organisms and the resulting GRSP (Curaqueo et al. 2011; Zhang et al. 2012). Thus, the application of NT can enhance soil quality in Eastern cape under sweet sorghum production as a biofuel feedstock. In addition, the application of residue retention can offset the negative impact of residue removal on aggregate binding agent.

The increase in aggregate binding agent is fundamentally important in the stability of aggregates (Zhang et al. 2014). Aggregate stability was positively correlated with both SOC ($r = 0.78$) and GRSP ($r = 0.84$) in the study (Malobane et al. 2021).

3.2 Steady State Infiltration Rate

The application of tillage, crop ration and residue management and their interaction had no significant effect on infiltration rate (Malobane 2020). This was in line with the previous studies by Jabro et al. (2016) and Blanco-Canqui et al. (2017). Therefore, the effect of tillage, crop ration and residue management or their interactions will need more than 3 years to see meaningful effects in eastern cape under sweet sorghum as a biofuel feedstock.

3.3 Bulk Density and Penetrometer Resistance

Tillage was the only factor that influenced BD and PR (Malobane 2020). The application of NT increased both BD and PR compared to CT treatment. The finds in this study were in line with previous studies (Celik et al. 2017; Bogunovic et al. 2018) (Table 2).

Table 2 Tillage effect on bulk density (BD) and penetrometer resistance (PR)

Tillage level	PR (kpa)	BD (g.cm ⁻³)
NT	3506.61a	1.67a
CT	2500.44b	1.61b

Note: NT: no-till, CT: conventional tillage. Values followed by the different letter within a column are significantly different at $P < 0.05$ level. (Adapted from Malobane 2020)

3.4 pH and Electrical Conductivity (EC)

The pH and EC showed no significant effects from tillage, crop rotation, residue management, or their interactions ($P > 0.05$) (Table 3).

3.5 Total, Organic and Inorganic (Ammonium (NH₄⁺-N); Nitrate (NO₃⁻-N)) Nitrogen

Tillage significantly influenced Total N, TON (Table 3). Compared to CT treatment, TN and TON were higher by 15.85% and 16.21%, respectively, under NT treatment (Malobane et al. 2020). The increase in TON and TON in NT management is typically attributed to the lack of soil disturbance and the retention of crop residues, which enhances soil organic matter (SOM) and promotes microbial activity associated with nitrogen fixation (Mazzoncini et al. 2016; Li et al. 2018). Crop rotation and residue management significantly influenced NH₄⁺-N and NO₃⁻-N (Table 3). In addition, tillage x residue management significantly influenced NH₄⁺-N (Table). Under the NT + 30% residue management treatment, NH₄⁺-N was 19.63% higher compared to the CT + 0% residue management treatment, which is commonly used in conventional farming (Malobane et al. 2020). Additionally, it is worth noting that increasing residue retention from 0% to 15% under the NT treatment resulted in a significant increase in N, which further increased at 30% (Malobane et al. 2020). In contrast, under the CT treatment, significant increases in N were only observed at the highest residue level (Malobane et al. 2020). The increase in available nitrogen (N) can be primarily attributed to the accumulation of organic matter in systems with crop residues (Mtyobile et al. 2019).

3.6 Available P

Residue management had a significant impact on available P, as shown in Table 3. Available P was significantly higher with 30% residue retention compared to total residue removal. Available P was 10.31% higher in 30% residue retention compared

Table 3 Electrical conductivity (EC), pH, total nitrogen (TN), total organic nitrogen (TON), ammonium (NH₄⁺-N), nitrate (NO₃⁻-N), available phosphorus (Available P), cation exchange capacity (CEC), calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) as influenced by tillage, rotation, residue management and their interaction

	EC	pH	TN	TON	NH ₄ ⁺ -N	NO ₃ ⁻ -N	Available P	CEC	Ca	Mg	K	Na
Till.	Ns	Ns	***	***	Ns	Ns	Ns	Ns	Ns	*	Ns	**
Rot	Ns	Ns	Ns	Ns	**	*	Ns	Ns	Ns	Ns	Ns	Ns
Res. man.	Ns	Ns	Ns	Ns	***	***	**	***	***	***	*	Ns
Till. × Rot.	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns
Till. × Res. man.	Ns	Ns	Ns	Ns	*	Ns	Ns	Ns	Ns	Ns	*	Ns
Rot. × Res. man.	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns
Till. × Rot. × Res. man	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns

Till: tillage, Rot.: Rotation, Res. man: Residue management, *, ** *** significant difference at 0.05, 0.01 and 0.001, probability level, respectively. (Adapted from Malobane et al. 2020)

to 0% residue management (Malobane et al. 2020). Residue retention increase substrate availability for micro-organisms that enhance P mineralization, thus, increase in available P (Yadav and Arora 2018).

3.7 Cation Exchange Capacity (CEC) and Extractable Bases

Tillage influenced Mg and Na, residue management affected CEC, Ca, Mg and K while tillage x residue managenet only impacted K (Table 3). The application of in 30% residue retention resulted in a higher CEC of 27.32% compared to 0 residue management treatment (Malobane et al. 2020). Furthermore, Ca was found to be.58% higher in the 30% residue retention treatment 0% residue management treatments (Malobane et al. 2020). NT + 30% residue management had 30.72% higher K compared to CT + 0% residue management (Malobane et al. 2020). In comparison to the residue removal treatment, the 30% residue retention treatment showed a 16.67% increase in K (Malobane et al. 2020). The NT treatment had a 45% higher Na compared to the CT treatment (Malobane et al. 2020). Residue management was found to be the main driver of soil fertility on marginal soils of Eastern cape under sweet sorghum as a biofuel feedstock. The increase in CEC, Ca, Mg and K is due to the increase in SOC under NT and residue retention compared to CT and residue removal (Murphy et al. 2016; Haruna and Nkongolo 2019).

4 Conclusion

In conclusion, this case study found that tillage is the primary factor influencing soil quality indices in marginal soils of South Africa under a sweet sorghum cropping system. The application of NT + 30% treatment combination was identified as a

potentially sustainable production system that can enhance soil quality indices in marginal soils of Eastern Cape under sweet sorghum as a biofuel feedstock. Long-term studies on NT + 30% are recommended in order to fully understand the benefits of this treatment combination on soil quality indices on marginal soils.

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Animal Feed Production and Its Contribution to Sustainability of Livestock Systems: African Perspective



T. P. Mamphogoro, T. D. E. Mpanza, and S. Mani

1 Introduction

African livestock forms about one-third of the global livestock population (AU-IBAR 2016) and contributes about 40% of the continent's agricultural GDP, with individual sub-Saharan countries varying from 30% to 80% in their contributions (Panel 2020). According to (Hidosa and Guyo 2017), livestock farming significantly alleviates household poverty and food insecurity. Over time, there has been a constant increase in global livestock production, which has increased the number of animals. However, these increases in animal population have not always been followed by better-feed resource availability for livestock, which may result in overgrazing, erosion, reduced health, and performance (Ravichandran et al. 2020). Feed quality and quantity combined with low producer prices have often forced farmers and feed producers to remain at low levels of animal feed production (Mengistu et al. 2017). It is evident that high global population growth, complemented by high future projections of demand for livestock products, stresses the need for higher animal productivity and increases in the number of animals. Inadequate feed quality and quantity inhibit increased animal production (Ntinyari and Gweyi-Onyango 2021).

T. P. Mamphogoro · S. Mani (✉)

GI Microbiology and Biotechnology Unit, Agricultural Research Council-Animal Production, Irene, South Africa

e-mail: ManiS@arc.agric.za

T. D. E. Mpanza

GI Microbiology and Biotechnology Unit, Agricultural Research Council-Animal Production, Irene, South Africa

Animal Nutrition Unit, Agricultural Research Council-Animal Production, Irene, South Africa

It is crucial to be prepared to produce adequate food for the high population based on locally available feed resources, especially in developing countries (US Census Bureau, 2008). Correspondingly, researchers have opportunities and challenges to increase animal productivity in quantity and quality by applying appropriate technologies in nutrition, production systems, and livestock feeding (Rusere et al. 2019). Feed is the essential input in all livestock production systems regarding cost. The availability of low-priced, high-quality feeds is critical if livestock production is to remain competitive and grows to meet animal protein demand (Adegbeye et al. 2020). Previous studies revealed that conventional methods of livestock improvement, such as breeding, livestock nutrition, and livestock disease management, have been used before and have increased livestock productivity (Dioha and Kumar 2020). However, these options can no longer sustain higher production independently; subsequently, new intensive techniques, including biotechnology, are now vital to supplement productivity (Balehegn et al. 2020). Modern biotechnology can open up new opportunities for increasing livestock output in a way that alleviates, improves food security and nutrition, and promotes the sustainable use of natural resources (Müller et al. 2017).

However, livestock production contributes significantly to global change with several negative environmental effects, including greenhouse gas (GHG) emissions, high water consumption, water pollution, acidification, air pollution, land degradation, and biodiversity loss (Thornton and Herrero 2015). Therefore, the sustainable intensification of animal production systems that provide economic and ecosystem services without compromising the future integrity, health, and welfare of the environment, animals, and humans has become a critical global research priority (Sumberg 2003). In Sub-Saharan Africa (SSA), improving the livelihoods of small farmers has become a primary goal, while alleviating negative environmental impacts is very important (Campbell et al. 2014). Improved livestock feeding and forages have previously been highlighted as a triple-win strategy for achieving climate-smart agriculture, increasing food security and resilience, and reducing GHG emissions (Thornton and Herrero 2010; Bryan et al. 2013; Peters et al. 2013).

Increasing competition for the requisite resources for feed production, particularly under more intensive animal production systems, has raised concerns about some animal production systems' economic and environmental sustainability (Herrero et al. 2013). Feed production, processing, and enteric fermentation of feed account for 45% and 39% of all agricultural GHG emissions (Steinfeld et al. 2006). Ruminants produce about 90% of animal emissions through enteric fermentation (188 million tons) and the remaining 10% from manure (Swamy and Bhattacharya 2006). In addition, poorly managed livestock production systems may have severe environmental impacts, including eutrophication in intensive, high-input systems, overgrazing and rangeland degradation in extensive systems, as well as adverse effects on human health (Mengistu et al. 2017; Adegbeye et al. 2020). Modern advances in livestock production have focused on developing the understanding of the nutrient requirements of animals and the improvement of feed quality. Therefore, we reviewed the improved sustainable approaches to animal feed production to increase food security and reduce greenhouse gas emission forces in Africa.

2 Sustainability of Livestock Production in Africa

In Africa, sustainable livestock production should simultaneously address issues of food security and climate change, in addition to social and economic factors (Balehegn et al. 2021). Nonetheless, this approach does not consider the livestock's nutrition, health, and other benefits in various production systems. These benefits compensate for the greenhouse gases they produce, which have decreased due to the introduction of improved livestock management systems (Capper 2011). The larger carbon footprint generated by livestock than other food sources is a necessary trade-off because livestock systems provide nutrient-rich products vital for health and well-being of humans (Herrero et al. 2016).

The need for and principles of sustainable livestock production apply universally. While many high-income countries focus on the environmental impacts of livestock production, low-income countries are concerned with increasing livestock productivity to increase food availability, grow revenue, and reduce the high incidence of childhood stunting and malnutrition (Tricarico et al. 2020). Most African countries rely on the Intergovernmental Panel on Climate Change (IPCC) tier 1 methodology to assess livestock-based emissions (Ammar et al. 2020). However, comprehensive and accurate data still need to be included, and precise estimates of natural resource use and environmental impact by livestock in Africa, particularly SSA, are rare.

The required resources for sustaining livestock production growth are limited, and future increases in livestock products must be accommodated using the existing resources, including land, water, and nutritious feed (Henry et al. 2018). Enhancing resource use efficacy while mitigating climate change impact is paramount for the sector's sustainability. The effects of climate change on livestock production depend on the extent and nature of the changes. They can be mediated through direct effects on the animal and indirect impacts on their environment, such as water availability, forage, and feed crop quantity and quality (Henry et al. 2018). Research has shown that rises in carbon dioxide levels, temperature, and nitrogen deposition reduce pastures' primary production (Tadesse 2018).

On the other hand, several already semi-arid areas are experiencing lower rainfall due to climate change. In many parts of the tropics, the pasture growing period is projected to decline due to significant variations in rainfall patterns and recurrent droughts (Hidosa and Guyo 2017). The changes in crop production are visible in feed resources for livestock production, as the quantity of available feed for the dry season feeding also reduces. The quality of plant material will be altered (from C3 to C4) as the temperatures increase, reducing the digestibility and leading to decreased nutrient availability for animals (Rust and Rust 2013).

The changes in seasonal patterns of forage availability have posed additional challenges for grazing management in rangeland; as rainfall decreases, it reduces yields and contributes to degradation (Hidosa and Guyo 2017). Similarly, the climates become hotter and drier, and the pasture composition is likely to shift to species that may be less suitable for grazing. The changes would alter the dietary

patterns of the livestock as they will significantly impact the type of animal species that can graze.

To mitigate the current limitations in feed resources, farmers could implement changes in response to pasture systems for feed production and sustainable livestock production. The changes include (i) selecting forage species such as deep-rooted grass mixtures in drought and water-logged soils (Thornton and Herrero 2010), (ii) managing grazing times and rotations (Ericksen and Crane 2018), (iii) adjusting inputs such as fertilizers and irrigation (Mekasha et al. 2014), (iv) farm system choices (cropping/pasture mix); these enhance the environmental and economic sustainability of the conversation agriculture system as a whole. The plant species must be functional for livestock fodder, grazing, and soil restoration. Lay crop systems can restore critical ecosystem functions by improving soil organic matter, fertility, and structure (Truter et al. 2015).

A crop-livestock integration will improve the sustainability of the whole farm and could provide multiple benefits and stability to the farm (Sumberg 2003). The crops and animals have a synergistic relationship where the crops provide feed residues and agro-industrial byproducts that the animals can utilize; animals provide manure to fertilize the soil and provide nutrients to the crops (Thornton and Herrero 2015). Economic and environmental benefits are often attained via crop-forage and livestock farming systems that improve land use and better income (Paul et al. 2020).

3 Feed Improvement for Livestock Production

3.1 Improve Feed Availability

Climate-smart livestock interventions improve productivity under resource-limited systems while improving climate change adaptation, mitigation, and environmental resilience (Gaitán et al. 2016). Climate-smart farm-level integration of various components of the livestock system reduces GHG and increases carbon sequestration, eventually contributing to a system-wide negative carbon balance (Ortiz-Gonzalo et al. 2017).

3.2 Agroforestry Systems

Carbon-neutral feed production techniques like silvopastoral and other agroforestry systems improve feed quality and carbon sequestration while lowering livestock GHG emissions. The technology uses farmlands, pastures, and degraded lands to grow trees that support diversification, the system's functioning, and resilience (Mutua et al. 2014). For example, compared to continuous corn cultivation, adding crop fodder tree plantations enhanced topsoil carbon by 141%. (Feliciano et al.

2018). This impacts pasture productivity, providing fodder biomass for surface retention and enhancing the field crops' nutrient status (Baudron et al. 2017). Integration of agroforestry systems is to be adopted in conditions of high soil fertility decline and soil erosion problems where fodder is scarce and in high demand (Thierfelder et al. 2018). Smallholder farmers are planting locally available shrubs and trees that produce nutritious fodder. It has contributed to rehabilitating degraded grazing lands, improving animal nutritional status, and improving goat productivity (Balehegn et al. 2014).

3.3 Grazing and Rangeland Management

Biomass production and biodiversity increase with appropriate grazing management (Savory and Butterfield 1998). In addition to the significant quantity of above-ground carbon stored in trees, bushes, shrubs, and grasses, grasslands that are well-managed store up to 260 tons of carbon per ha, as rangelands can hold up to 30% of the world's soil carbon (Grace et al. 2006). Most pasture and rangeland soils in Africa do not produce forage to their biological potential due to overgrazing, soil degradation, and pastureland mismanagement (Boote et al. 2022). Treatments like rotational, moderate, and zero grazing, which protect the degraded area and allow natural regeneration of forage and improvement of forage production, make it possible to increase livestock productivity and carbon sequestration by grazing lands (Gebregergs et al. 2019). These improve the productivity of grazing land and the quality of forage produced and reduce land degradation. Furthermore, an in-depth search is required to comprehend how to manage grasslands to facilitate carbon capture and what mechanisms can support such management practices.

3.4 Improved Forage-Based Systems

As opposed to feedlots, perennial, low-input fodder systems can typically sequester a substantial amount of carbon (Peters et al. 2012). About 4% of the potential global agricultural GHG mitigation comes from forages cultivated in low-income countries (Thornton and Herrero 2010). The advantage of forage-based systems is evident with improved forages as they increase herbage biomass and livestock productivity, especially in the dry season (Paul et al. 2020). Climatic conditions influence the growing season in tropical and sub-tropical regions; hence, it is seasonal bound. Vegetative growth of plants and grasses in the tropics is active during the wet season based on conducive growing conditions such as ambient temperature, soil moisture contents and light intensity (Mpanza and Hassen 2023). Therefore, climate change significantly impacts forage production in sub-Saharan Africa; about 20% of pasture production is predicted to be lost by 2080 due to climate change (Shah et al. 2008). This is because livestock farming ruminants under

smallholder farmers solely depend on natural pasture as the significant feed source (Amole and Ayantunde 2016; Boone et al. 2018), which is characterized by low quantity and quality (Boone et al. 2018; Amole et al. 2022).

On the other hand, trees and shrubs are resilient to climate change; thus, they offer an alternative feed source for animals during the dry season (Table 1). Hence, legume fodder trees and shrubs have been evaluated as an alternative feed source to improve animal fodder bank management (Amole et al. 2022). This is because tree fodder as a fodder bank can provide necessary nutrients such as protein, vitamins and minerals, especially during the dry season (Kubkomawa et al. 2019; Raj et al. 2023) (Raj et al. 2023). The presence of essential elements such as calcium, sodium, sulphur, iron and zinc are the most lacking minerals in grass forage (Jamala et al. 2013; Raj et al. 2023). Subsequently, browsing legumes (trees and shrubs) is crucial in livestock maintenance and survival (Jamala et al. 2013).

Multispecies fodder bank projects have been implemented in some African countries like Ghana as a climate-smart option to improve livestock nutrition by ensuring sustainable fodder production and availability throughout the year. This is an innovative approach that all African countries can adopt to sustain feed availability during the fodder scarcity period.

3.5 *Conserving Natural Ecosystems*

Pasturelands contain better soil carbon concentration than croplands and even forests by 59% and 10%, respectively, indicating a more significant potential for soil carbon sequestration (Guo and Gifford 2002). Compared to a freely grazed area, degraded grasslands not subjected to grazing, cultivation, and other disturbances result in a 187% increase in carbon stock (Berhe et al. 2020). Zero grazing on degraded fields may improve the soil and increase above-ground carbon sequestration. However, despite its potential, pastoral ecosystems, like those in SSA, can play a role in reducing atmospheric greenhouse gas emissions by sequestering carbon is rarely recognized (Gebregergs et al. 2019). Forage plants are introduced in natural resource conservation structures to reinforce soil and water conservation while serving as a feed resource. This protects the land degradation and soil loss while improving feed availability (Mengistu et al. 2017).

3.6 *Other Interventions*

Additional interventions that can help minimize the environmental impacts of livestock in SSA include manure management, housing, improved water use efficiency, animal health, and genetics (Knapp et al. 2014). Reducing the number of unproductive animals in Africa and replacing them with fewer but more productive ones will minimize livestock's adverse environmental effects, including GHG emissions.

Table 1 Chemical composition of commonly used fodder trees as feed source for livestock

Plant species	DM	Ash	CP	Energy	CF	P	K	EE	NDF	ADF	Source
<i>Colophospermum mopani</i>	93.74	3.96	16.33	22.67	–	–	–	–	–	–	Kujoana et al. (2023)
<i>Morus indica</i>	81.30	6.8	16.74	–	27.39	0.61	0.79	–	–	–	Raj et al. (2023)
<i>Sclerocarya birrea</i>	85.67	5.43	10.33	17.10	–	–	–	–	–	–	Kujoana et al. (2023)
<i>Terminalia pruntoides</i>	93.61	7.76	8.50	16.73	–	–	–	–	–	–	Kujoana et al. (2023)
<i>Leucaena leucocephala</i>	90.63	5.9	18.51	–	29.95	0.52	0.61	–	–	–	Raj et al. (2023)
<i>Vachellia galpinii</i>	93.29	2.67	14.97	16.84	–	–	–	–	–	–	Kujoana et al. (2023)
<i>Spondia mombia</i>	89.50	5.59	17.84	–	16.76	–	–	3.21	–	–	Lamidi and Ologboso (2014)
<i>Albizia Zygia</i>	86.00	4.68	24.21	–	20.10	–	–	2.93	–	–	Ologboso (2014)
<i>Capparis tomentosa</i>	95.33	7.31	18.90	12.67	–	–	–	–	–	–	Kujoana et al. (2023)
<i>Moringa oleifera</i>	29.79	8.96	20.06	–	28.12	0.28	1.04	–	–	–	Raj et al. (2023)
<i>Vachellia tortilis</i>	93.20	3.13	14.93	18.73	–	–	–	–	–	–	Kujoana et al. (2023)
<i>Dichrostachys cinerea</i>	94.20	2.22	14.93	9.90	–	–	–	–	47.90	47.40	Raj et al. (2023)
<i>Gliricidia sepium</i>	86.37	7.44	19.99	–	23.72	0.19	0.92	–	–	–	Raj et al. (2023)
<i>Ziziphus mucronata</i>	93.83	8.93	18.63	15.20	–	–	–	–	37.00	26.90	Kujoana et al. (2023)
<i>Maerna angolensis</i>	89.86	13.98	21.81	16.97	–	–	–	–	–	–	Kujoana et al. (2023)
<i>Cajanus cajan</i>	93.05	8.47	18.56	–	19.23	–	–	7.06	–	–	Lamidi and Ologboso (2014)
<i>Centrosema pubescens</i>	92.49	9.36	20.44	–	19.43	–	–	3.83	–	–	Ologboso (2014)

(continued)

Table 1 (continued)

Plant species	DM	Ash	CP	Energy	CF	P	K	EE	NDF	ADF	Source
<i>Vachellia mellifera</i>	91.9	12.6	12.6	–	–	–	–	–	33.7	19.4	Shenkute and Hassen (2012)
<i>Celtis Africana</i>	88.1	20.6	15.1	–	–	–	–	–	30.4	24.9	
<i>Ficus gnaphalocarpa</i>	88.30	18.30	10.80	–	–	–	–	–	53.60	44.00	
<i>Vachellia mellifera</i>	91.90	12.60	12.60	–	–	–	–	–	33.70	19.40	
<i>Piliostigma reticulata</i>	–	7.34	11.80	–	–	–	–	–	69.40	69.40	
											Amole and Ayantunde (2016)
<i>Faidherbia albida</i>	90	–	–	–	1.1	–	–	–	41.8	30.7	Davy et al. (2023)

DM Dry matter, CP Crude protein, CF Crude fiber, P Phosphorus, K Potassium, EE Ether extract, NDF neutral detergent fiber, ADF Acid detergent fiber

However, the method is particularly at odds with the goals of African farmers who favour keeping more animals for non-economic purposes (Forabosco et al. 2017). An option is to use underutilized feed resources, such as indigenous fodder species, to improve feed availability. *Ficus thonningii* is an example of an underutilized fodder tree in many countries in sub-Saharan Africa. It can replace expensive concentrates as it is locally and economically available (Balehegn et al. 2014).

3.7 Improving the Quality of Feeds

Most African ruminant diets consist of natural pasture of low-quality crop residues, accounting for about 72% to 93% of total feed consumed by livestock. (FAO 2014). Therefore, it is necessary to adopt crop residue (Straw) improvement technologies, such as chemical treatment with urea/ammonia and other treatments, including biological or physical treatment. This could increase intake and digestibility while potentially lowering enteric CH₄ emission intensity (Owen et al. 2012; Balehegn et al. 2021). However, the development and implementation of these residue improvement technologies in smallholder production systems in SSA have been constrained by financial limitations (Owen et al. 2012).

3.7.1 Physical Crop Residue Treatment

Techniques such as chaffing, chopping, and grinding roughage or fibrous feeds have also reduced enteric CH₄ emissions by about 10% through improved feed intake and digestibility (Valli 2020). Chopping is the most common physical treatment used by smallholder farmers to minimize wastage, avoid selective feeding, and maximize feed utilization (Owen et al. 2012). Chopping also increases the intake of roughages, improving the overall feed use efficiency to improve productivity. Crop residues can also be grounded and mixed with other feeds and made into pellets or fed to animals directly. These practices are reported to increase feed intake and the overall efficiency of feed utilization. Similarly, pelleting reduces feed waste by up to 5%, thus reducing emissions (Carter et al. 2012).

3.7.2 Chemical Treatment

The chemical treatment of crop residues enhances feed quality by treating crop residues to improve feeding values. Urea has been utilized, and the technique is very appropriate for many developing countries due to its ease of applicability and utilization. The treatment procedures are simple; urea is accessible for most smallholder farmers and does not pose any adverse health effects on animals and humans, making it more beneficial. Urea improves crop residues' crude protein and digestibility (Berhe et al. 2020). Ammonization and alkali treatment of roughages reduce

methane intensity by increasing animal productivity. However, urea treatment is more widely used than alternatives and has the most significant potential for uptake when considering chemical treatments' prices, risks, and effectiveness (Woyengo et al. 2004). In comparison to conventional diets (untreated straw), using urea-treated crop residues in ruminant diets reduced GHG emissions by 1.02 Mt. CO₂-eq annually (5.5%) in Ethiopia and 3.18 Mt. CO₂-eq annually (8.8%) in Kenya (Pressman et al. 2018).

3.7.3 Biological Treatment

The biological treatment of crop residues involves using beneficial microbes such as lactic acid bacteria, photosynthetic bacteria, yeast, and enzymes to help increase the digestibility of fibrous feeds by directly producing enzymes, amino acids, and organic acids inside the digestive system of the animals (Mahesh and Madhu 2013). Most treatments are used in silage-making to prevent nutritional loss and spoilage (Balehegn et al. 2022). Sometimes, they inhibit spoilage organisms from contaminating the feed resources.

The quality of crop residues can also be improved by crop breeding, particularly when enhancing the digestibility of dual-purpose crops. Different fibrous diets have different levels of digestibility, and, as such, they differ in their methane emission. (Giger-Reverdin and Sauvant 2000). Crop breeding to increase the nutritional value of crop leftovers can improve crop quality, increase animal output, and lower emission levels. However, it is paramount to ensure that crop breeding for improving crop residue quality simultaneously increases grain yield. If not, such measures will not succeed, with African smallholder farmers prioritising food production above feed. (Adesogan et al. 2020).

3.8 Maintenance of the Feed Quality

Forage preservation is a significant solution to ensure the nutritional quality of feed available across seasons (Balehegn et al. 2022). Reduction in the availability of forage and nutritional value occurs across the continent, limiting the nutrient supply required to optimize the growth and productivity of livestock. In the highlands of Tanzania, CP and ME forage values decreased by 20% in the dry season, leading to a decrease in milk yield by 40% from forage-fed cows (Maleko et al. 2018). Forage preservation and conservation practices are critically required to preserve the quantity, minimize nutrient energy loss and reduce spoilage. Commonly preserved forages in Africa are planted forages, crop residues, and herbaceous vegetation from natural pastures (Ajayi 2011). The forage types' significance and preservation techniques differ with farming systems and the farmer's socioeconomic status.

3.8.1 Haymaking

Preserving forage as hay is common among commercial and smallholder farmers across African countries. Even pastoralists are now practising storing grass in the form of hay due to increasing climate variability (Balehegn et al. 2022). The production quality levels are usually low due to late harvesting, using native poor quality forage (Kitaba and Tamir 2007), and improper storage (Feyissa et al. 2013). Most smallholder farmers store hay in open fields, causing a loss of up to 70% of crude protein due to leaching (Yayneshet et al. 2009). Hay nutritional quality significantly differs in various forage species and the harvest time; legume hay produced in South Africa is high quality in crude protein compared to grass and cereal hays (Müller et al. 2017). Natural pasture hay has a lower quality than improved forage hay due to the utilization of natural vegetation with different degrees of forage quality and outdoor stockpiling for storage, leading to loss of nutrients (Feyissa et al. 2013).

There are several recommended interventions to improve hay quality and storage. A study in Ethiopia suggested that farmers should harvest hay before complete maturity and create a platform with stone or wood for proper storage off the ground after drying to avoid spoilage. Hay should be shaded to protect it from the sun, encouraging a legume-grass mixture for better nutritional quality (Suttie 2000; Balehegn et al. 2022).

3.8.2 Silage Making

Silage is a fermented, high-moisture forage stored under anaerobic and acidic conditions to preserve the quality. Silages generally have a higher moisture concentration ranging between 650 g⁻¹ kg compared to hay, of about 8 and 150 g⁻¹ kg, because they are not dried before preservation and at times at an earlier growth phase compared to hay (Müller et al. 2017). However, in sub-Saharan Africa, silage is mainly prepared on large commercial farms or under experimental conditions in research farms and universities (Balehegn et al. 2022). Insufficient inputs, high costs, awareness, and technical knowledge hinder smallholder farmers' adoption of silage production (Twinamatsiko et al. 2020). Commercial farms mainly prepare silage using maize, elephant grass, sorghum, barley, and oat forages ensiled in large bunkers (Müller et al. 2017), while urban and peri-urban farmers primarily use pit silos or small bags from different forages. Napier grass and maize are the primary ensiled forages in East Africa for dairy production (Creemers and Aranguiz 2019).

3.9 Improving the Nutritional Status of Animals

Strategies for improving nutritional status include supplementation with concentrates, ration balancing, and additives to improve feed use efficiency and reduce enteric CH₄ emissions.

Ration formulation. Animals in most small-scale production systems in Africa are fed whatever is available without meeting the feed quality and animal requirements (Balehegn et al. 2020). In dairy cows, balancing the ration has been shown to lower gross energy loss through CH₄ by 10.3% and milk emission intensity by 13.5%. (Garg et al. 2013). Balancing protein requirements reduces excess nitrogen excretion, reducing N₂O emissions through manure (Cole and Todd 2009). However, the reduction of dietary protein for dairy cattle must be closely monitored to avoid negatively affecting milk production. Proper use of ration-formulation technology requires understanding and accurately quantifying the nutrient requirement of *Bos taurus* breeds such as Holstein-Friesian (Nozière et al. 2018).

Supplementation. The overall low livestock productivity in SSA is mainly due to the nutritional inadequacy of rations. This can be addressed by providing supplementary nutrients and energy by substituting low-quality feed with other high-quality feed (Balehegn et al. 2021).

Studies have shown that the strategic use of tree fodder as animal feed ingredients has resulted in a positive result. Cohen-Zinder et al. (2017) conducted a study on dairy cow-fed *Moringa oleifera* silage and showed improved milk yield with reduced somatic cell count (SCC). Furthermore, they reported a significant improvement in milk antioxidants in dairy cows fed *Moringa oleifera* silage. Kekana et al. (2019) reported a significant increase in milk fat with reduced somatic cell count in dairy cows supplemented with *Moringa oleifera* meal. Hao et al. (2020) reported a substantial improvement in feed intake, milk protein content, and a reduced somatic cell count on a Holstein dairy cow-fed diet with *Broussonetia papyrifera* silage. As reported in these studies, the improved antioxidant in milk with reduced somatic cell count translates to the quality and healthiness of the milk to human beings.

A study that was conducted on Woyto-Guji goats (weaners) showed that animals that were given dietary treatment that contained 35% of Lablab forage performed better compared with another group in terms of nutrient digestibility, weight gain, feed use efficiency and carcass characteristics (Hidosa et al. 2018). Replacing concentrate with *Moringa oleifera* silage modulates rumen fermentation by significantly increasing the rumen pH while reducing ammonia nitrogen and increasing milk yield and composition (Kholif et al. 2022). Furthermore, feeding *Moringa oleifera* silage in goats reduced oxidative stress while improving milk's energy content and quality by increasing serum antioxidant capacity, glucose and total conjugated linoleic acids (Kholif et al. 2022).

Sheep supplemented with the mixture of *Leucocephala* and *Somania* foliage at the proportion of 1:1 performs better in feed intake and weight gain (Idan et al. 2023). Feeding *Broussonetia papyrifera* silage in Hu sheep was reported to modulate rumen fermentation and biohydrogenation by promoting the dominance of bacteria *Christensenellaceae_R-7_group* (Xiong et al. 2021). The dominance of the *Christensenellaceae_R-7_group* in the rumen is associated with the reduction of unsaturated fatty acid degradation, particularly n3-polyunsaturated fatty acid. This is because this bacteria reported a significant positive correlation with n3-polyunsaturated fatty acid (Xiong et al. 2021; Wang et al. 2023). It has been shown that replacing crop residues with legumes such as *Crotalaria juncea* L., *Cajanus*

cajan Millsp., *Moringa stenopetala* Cuf., *Leucaena leucocephala* de Wit., *Sesbania sesban* Merr., and *Lablab purpureus* L. reduced enteric CH₄ production by 8–26% (Berhanu et al. 2019). The primary problem with supplements is the high cost of nutrient-dense ingredients due to importation or food-feed competition (Mottet et al. 2018). Therefore, increased domestic production of such ingredients is critically needed to reduce production costs by smallholder farmers.

4 Conclusion

Livestock are vital sources of livelihood and nutrition to millions of smallholder farmers in sub-Saharan Africa, contributing about 40% of the continent's agricultural GDP. However, the limited supply of quality feed resources is the main restriction in developing African livestock systems, limiting the accessibility of food and nutritional security. The successful adoption of feed enhancement techniques relies on capacity building by providing farmers with training and access to information. As most smallholder farmers lack a proper understanding of feed quality and ways to improve it, awareness of the importance of enhancing forage quality and profits is necessary. Therefore, there is a need to use land based on its capabilities to improve the amount and quality of feed available to enhance performance and productivity toward effective use of accessible feeds. Alternative means of traction and improving the efficiency of site-specific feed conservation strategies through research and development interventions to support the productive stock in the respective eco-environments are required. Alternatively, there is a need to encourage the production of fodder diet plants not widely consumed by humans, such as *Moringa oleifera* and *Broussonetia papyrifera* silage and *Leucocephala* and *Somanea* foliage, to provide high energy and high protein feed for dairy, marketing of these fodder plants should be. We recognize that this will compete with land use for dual-purpose food-fodder crops, but it provides high-quality feed for high-value dairy and other livestock farming.

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Replenishing Marginal Soils Through Use of Agroforestry Systems in Southern Africa: A Case Study of Pigeonpea (*Cajanus cajan* L. Millsp) Improved Fallows in South Africa



M. Musokwa and T. Chavhunduka

1 Introduction

Extension of agricultural lands to marginal lands to enhance food security and farmers' income, has received a lot of recognition worldwide. Coming up with a definition of marginal land is a complex piece of work that cannot be restricted to the biophysical quality of the land. The term marginal land originated in the early nineteenth century in the Theory of Rent from Ricardo, D. (Ricardo 1817). Complex scientific research of lands' low productivity was initiated in the nineteenth century. Peterson and Galbraith 1932 devised a modern theory of marginal land categories in the circumstances of a modern land use planning theory. Because of population increase and weather extremes due to climate change, more conscious and sustainable land use planning has become even more vital for the past decades, that needs the theories of prime land and marginal land to be revived on regular basis (Kang et al. 2013). Definitions of marginal land as well as its application realms vary within regions, countries, and organizations because of their divergent aims (Esch et al. 2018; FAO 2008; Gopalakrishnan et al. 2011; Tang et al. 2010). The similar characteristics that make a site "marginal" in one area or for one aim could make land productive in another area or for a divergent motive (Dale et al. 2010; James 2010). Soil Scientists normally define marginality as loss of physical and productivity of soils. They use the factors that affect crop yield, which include soil sodicity, water management salinity. Physical properties are becoming primary indicators of marginality. Other affected lands are not only low in productivity, but also have limits that avert them from being utilised for traditional farming practices (Jones et al. 2014; Schubert et al. 2008). Hence, they may be considered as Less Favoured Areas, that may be expressed as marginal land (Confalonieri et al. 2014; Jones et al. 2014).

M. Musokwa (✉) · T. Chavhunduka

The Southern African Confederation of Agricultural Unions, Pretoria, South Africa

Land in Africa is increasingly degrading (UNEP 2008). Erosion, chemical and physical damage has degraded about 65% of agricultural land (UNEP 2008). This has forced farmers to cultivate marginal lands. There are various threats to soil health and ecosystem services in southern Africa (SA). These include soil erosion by water and wind, loss of soil organic matter (SOM), soil nutrient depletion, loss of soil biodiversity, compaction, crusting, sealing/capping (FAO and ITPS 2015). Barbier and Hochard (2016) showed that approximately 28% of rural Africa's farmers cultivate land that is degrading over time. Land degradation is defined as the loss of production capacity of land in terms of loss of soil biodiversity, soil fertility and natural resources degradation (FAO 2002). Extensive land degradation is generally caused by agricultural mismanagement, overgrazing and deforestation due to population pressure, which have led to farmers using land more extensive and cultivate on marginal areas (Gichangi et al. 2016). Agricultural land is degrading at a faster rate and losing its productivity because of soil erosion and nutrient depletion associated with continuous cropping without soil conservation and nutrient addition (AGRA 2016). Continuous land deterioration does not only pose a threat to food security, but also enhances climate change by denuding vegetative ground cover and depleting SOM. Low yields among smallholder farmers on the other hand are partly due to diminishing soil fertility. The soils have low organic matter (OM) content due to poor natural vegetation cover and removal of crop residues for livestock feeding. These fields have low soil fertility and organic matter, and they have limited water holding capacity and are vulnerable to massive erosion. All forms of land and soil degradation can be reversed through adoption of agroforestry systems (AFS) for soil conservation and rehabilitation (Mafongoya et al. 2006). Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos etc) are deliberately used on the same land management unit as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In AFS, there are both ecological and economic interactions between the different components (van Noordwijk 2019). Through AFS, nutrient cycling can be improved, soil physical properties, soil biodiversity as well as soil organic matter can be enhanced (Musokwa et al. 2020; Sileshi et al. 2014). Agroforestry practices can be seen as an alternative or complement to the use of fertilisers, especially in SA where fertilisers are not always available and when available their high cost usually limits their use by smallholder farmers (Bationo and Waswa 2011; Sileshi et al. 2014). Various studies have argued that agroforestry legume-tree species such as pigeonpea can be used to rehabilitate degraded lands as well as enhancing yields of cereal crops (Kuyah et al. 2019; Mugi-Ngenga et al. 2021; Musokwa et al. 2020). A meta-analysis of 94 peer reviewed publications across southern African countries (Sileshi et al. 2008), showed that maize yields doubled compared to continuous unfertilised maize. In highly degraded soils, agroforestry legume tree species such as *Cajanus cajan* L. Millsp (pigeonpea) have been reported to increase productivity in a relatively short period (Musokwa et al. 2020). This chapter seeks to provide smallholder farmers in SA with information on marginal soils or soil fertility degradation, which may be replenished using agroforestry systems. A case study of pigeonpea improved fallows used in South Africa to

replenish degraded soils and increase maize yields under smallholder farming conditions will be used to demonstrate this.

2 Soil Fertility Degradation and Its Impacts

Biological degradation is often identified through the reduction of OM in the soil and vegetation cover, but it also indicates the depletion of biological activity (Hartemink and Van Keulen 2003). It emanates from unsuitable soil management practices that lead to chemical and physical soil degradation. Soil fauna is an indicator of soil fertility status and affect soil structure (Musokwa et al. 2020). The depletion of the structure of the soil through compaction or crusting and water logging, hinders aeration and consequently the provision of oxygen to the aerobic soil organisms (Mitiku et al. 2006). The curbing of biological degradation of the land can be achieved through ensuring that the land is protected by desirable trees or shrubs.

Various chemical processes that diminish soil fertility includes reduction of plant nutrient reserves as well as enrichment of substances that are toxic (Hurni 1993). According to Mitiku et al. (2006), because of leaching, especially in the humid areas, soluble nutrients emanating from the root zone can be washed out. Acidification produces aluminium and ferrous oxides resulting in phosphorous fixation, that is rendered unavailable for absorption by plants and is one of the implications of chemical degradation of the soil (Hartemink and Van Keulen 2003). Organic matter guarantees favourable physical soil conditions for processes such as water retention (Mitiku et al. 2006). It supplies balanced and slow-flowing sources of nutrients and is a basis for the cation exchange capacity (CEC). Farming systems that involve periodic tillage, enhance OM depletion, frequently within a few cropping cycles, OM depletion is one of the major chemical degradations of the land because it is the major constituent for the growth of the plants and for productivity. Consequently, one of the sustainable land practices that can restore soil fertility of the land, is through use of legume tree/shrub-based farming systems. The extent and rate of soil fertility degradation in Southern Africa is still under debate as there are no reliable data, just gross approximations (Tully et al. 2015). It is estimated that roughly 15% of the land in Southern Africa is experiencing soil degradation through erosion (SADC 2008), a trend shared with sub-Saharan Africa (Tully et al. 2015). This trend in land degradation is likely to continue over the next decades, because of population pressure, skewed land tenure systems and increasing demand for land from diverse sectors.

3 Soil Fertility Replenishment Through Agroforestry Systems

Soil fertility is defined as the ability of the soil to support the growth of plants, in a sustainable manner under a given environment and other suitable properties of the land (McGrath et al. 2014). Soil fertility reduction results from the integrated effect of reduced soil OM, declining of physical properties, lowering of nutrient content, and in some cases acidification, that is commonly associated with the decline in soil fertility (McGrath et al. 2014). Comparably, low soil fertility is the main challenge to food production and one of the major biophysical constraints to increased agricultural growth in SA. AFS plays a significant role in soil fertility replenishment. Agroforestry systems that replenish soil fertility are classified into different types i.e., fallows, hedgerow, alley cropping, tree on cropland, plantation on physical structures. Legume tree species or fertiliser trees have exhibited some potential for soil fertility amelioration since soil fertility improvement can be attained via litter addition, litter decomposition and nutrient release, nutrient addition through root biomass, biological nitrogen fixation and nutrient pumping (Zhang et al. 2020).

There are numerous agroforestry trees species that can be used for improved fallows in Southern Africa. Agroforestry legume tree species have shown to improve productivity under marginal lands in Southern Africa as shown in Table 1.

Table 1 Some examples of improved fallows which were tested in Southern Africa

Country Site	South Africa Wartburg	Zimbabwe Domboshava	Malawi, Makoka	Zambia, Msekera
Latitude/longitude	29°27' S 30°32' E	19°35' S 31°14' E	15°30' S 35°15' E	13°39' S 32°34' E
Altitude (m)	853	1474	1030	1030
Average rainfall (mm)	850	750	1024	925
Average temperatures	14–29 °C 5–22 °C	15–28 °C 7–21 °C	19–34 °C 10–21 °C	22–29 °C 11–16 °C
Soil type (FAO class)	Ferralsols	Lixisols	Ferric Lixisols	Haplic luvisols
Soil texture (%) clay: Sand	16: 75	22: 71	37: 52	25: 67
Organic carbon (%)	0.65	0.54	1.33	0.4
Agroforestry tree species used	<i>Cajanus Cajan</i> (Pigeonpea)	<i>Acacia</i> <i>angustissima</i> <i>Sesbania sesban</i>	<i>Gliricidia</i> <i>sepium</i> , <i>Cajanus</i> <i>Cajan</i>	<i>Sesbania</i> <i>sesban</i>
Maize yields as compared to traditional monoculture	Tripled	Doubled	Double	Doubled
References	Musokwa et al. (2020)	Mafongoya and Dzowela (1999)	Chirwa et al. (2007)	Phiri et al. (2003)

3.1 Litter Addition, Decomposition and Nutrient Release

Litter constitutes a substantial aggregate of nutrients required for plant growth and functions as a main ingredient of nutrient cycling in AFS (Zheng 2006). Litter production and decomposition returns OM as well as nutrients from aerial parts of the plants to the soil surface to enhance soil fertility. Leaves, twigs, bark in addition to amorphous matter of fertiliser tree species are the key constituent of litter production in AFS. The litter production in AFS mostly relies on the nature of tree-crop species and other factors, which include climatic, edaphic, topographic and biotic as they influence plant growth and phenology (Rawat et al. 2009). The crop species contributes less than perennial woody tree species in terms of entire litter production in AFS. Deciduous species contribute huge quantities of litterfall than ever-green species because of litterfall that is available all the time. After litter production, litter decomposition and rate of decomposition has great significance in sustaining the soil fertility. To release nutrients, litter should be broken down and decomposed. Soil fauna moderate litter decomposition and mineralisation. Decomposition rate of litter is controlled by interactivities between the litter quality, decomposers as well as physical environment of the site (Zheng 2006). The floral diversity of AFS generates conducive environment for soil microbes, that performs a key function in litter decomposition and release of nutrients (Kumar 2011). Litter quality denotes to intrinsic chemical as well as structural properties that control the undertakings of decomposer organisms, that to a certain extent regulates the decomposition rate of OM. The chemical characteristics of the litter include nitrogen content, C:N ratio, phosphorus content, C:P ratio, phenolics, phenolics to N or P ratio, lignin content and lignin to N ratio. Litter nutrients release relies not only on litter make-up but also soil type, microbial communities, and soil characteristics. The high values of C:N ratio, C:P ratio, phenolics, phenolics to N or P ratio, lignin content and lignin to N ratio are lower the decomposition rate, in contrast to, high nitrogen and phosphorus content which speed up the rate of decomposition (Rawat et al. 2009). Nutrients exuded from the fine root biomass are another vital mechanism of ameliorating soil nutrient health. Trees assign a substantial part of total primary production belowground for the production and maintenance of roots as well as mycorrhizae (Nair et al. 2009). In such environment SOC increase and improve soil characteristics (Table 2).

3.2 Biological Nitrogen Fixing (BNF)

Increasing use of N fertilisers in intensive agriculture reduces its use efficiency as well as leading to environmental challenges. Most smallholder farmers are occupying marginal lands in SA and cannot afford to purchase nitrogen fertilisers hence their yields are very low. The atmospheric biological nitrogen fixation (BNF) has

Table 2 Soil Organic Carbon fixed in different improved fallow systems from some Southern Africa African countries (Adapted from Chirwa et al. 2023)

Country	Fallow Tree species	SOC stocks (Mg ha ⁻¹)	References
Zambia	Copping fallows	32.2–37.8	Kaonga and Coleman (2008)
Zambia	Non-copping fallows	29.5–30.1	Kaonga and Coleman (2008)
Zimbabwe	<i>Acacia angustissima</i>	26.3	Nyamadzawo et al. (2008)
Zimbabwe	<i>Sesbania sesban</i>	25.4	Nyamadzawo et al. (2008)
Tanzania	<i>Acacia crasscarpa</i>	15.8	Kimaro et al. (2009)
Tanzania	<i>Acacia mangium</i>	25.6	Kimaro et al. (2009)
Tanzania	<i>Acacia polyacantha</i>	21.6	Kimaro et al. (2009)
Tanzania	<i>Gliricidia sepium</i>	18.8	Kimaro et al. (2009)
Tanzania	<i>Acacia nolotica</i>	22.7	Kimaro et al. (2009)

Table 3 Agroforestry tree species with their nitrogen fixing capabilities in Southern Africa (Adapted from Nair 1993)

Agroforestry tree species	Nitrogen fixed (kg N/ha/yr)
Apple-ring Acacia, Ana Tree (<i>Faidherbia</i> (<i>Acacia</i>) <i>albida</i> (Delile) A. Chev.)	20
Gliricidia (<i>Gliricidia sepium</i> (Jacq.) Kunth ex Walp.)	13
Subabool, Ipil-ipil (<i>Leucaena leucocephala</i> (Lam.) de Wit.)	100–500
Pigeon pea (<i>Cajanus cajan</i> L. Millsp.)	68–88
Dhaincha (<i>Sesbania sesban</i> (Jacq.) W. Wight)	7–18
New Dhaincha (<i>Sesbania rostrata</i>)	70–458

nutrient cycling capability in AFS and plays a fundamental function in solving some of these problems (Table 3).

Biological Nitrogen Fixation (BNF) occurs via symbiotic and non-symbiotic mechanisms. Symbiotic fixation happens the interconnection of plant roots with nitrogen-fixing microorganisms. Most legumes form an interconnection with the bacteria rhizobium which helps in nitrogen fixation. Legumes form roots nodules with two types of rhizobia, which include rapidly multiplying strains (genus *Rhizobium*), and slowly-multiplying (genus *Brady rhizobium*) strains. BNF is moderated by nitrogenase enzymes in soil and relies on ecological environment in connection with the certain nitrogen fixation capabilities of specific microorganisms and plant genotypes in contrasting climatic environments (Shridhar 2012). Based on the improvement in resource use efficiency, the use of nitrogen-fixing trees in combination with non-N₂-fixing annual crop species enhances the nitrogen availability on nitrogen-scarce sites.

3.3 *Nutrient Pumping*

Tree root systems play a major role in carbon enrichment in soil via root turnover, the interception of leached nutrients, or the physical improvement of compacted soil. The assumption is that the trees have deep and spreading roots, which could extract nutrients and water from deeper soil horizons where annual crop roots would not normally reach. This process of extracting nutrients from deeper soil horizons and subsequently availing them on the surface layers via litter-fall and other processes is known as ‘nutrient pumping’ by trees. This mechanism mostly relies on properties of tree species as well as other soil, climatic and topographic factors. Trees growing on low moisture content soils have deep root systems and aid in nutrient and water pumping than soils with higher moisture content (Makumba et al. 2006).

3.4 *Agroforestry Systems on Soil and Water Conservation*

Agroforestry systems can curb erosion through the provision of leaf litter, tree canopy as well as the function of trees in relation to runoff-barrier role (Nair 1993). In the same way, Ajayi et al. (2008) reported that trees/shrubs improve the physical properties of soils. Specifically, soil aggregates are far much higher in fields where AF is practised as compared to degraded lands, and this improves water infiltration as well as water holding capacity of soils as a result water runoff and soil erosion is reduced. The functions of the trees and shrubs in controlling erosion can be classified into two categories i.e., direct or complementary function. In direct use, the AF trees curb runoff and soil loss. While in supplementary use, control is attained mainly through other mechanisms such as ditch and-bank structures, grass strips and terraces. The trees assist in stabilising soil structures including the productive utilisation of the land that they occupy. According to (Nair 1993) and AF trees have shown potential of diminishing soil erosion through 5 main pathways:

- Enhanced water infiltration.
- Formation of erosion resistant soil structure.
- Interception of rainfall drop impact by tree canopy.
- Surface runoff impediment by tree stems.
- Soil surface cover by leaf litter.

Udawatta et al. (2002) highlighted that AFS and contour strip offers an integrated impact on runoff, sediment as well as reduction of nutrient loss than treatments with no AFS. Comparably, Okigbo and Lal (1985) argued that the protection measure entails the utilisation of vegetation for soil protection, sustains the hydrological balance so that the surface run-off constituent in the hydrological cycle would be reduced. In the same way, Juo and Thurow (1998) argued that vegetative barrier is normally utilised in conjunction with mechanical land treatments which include

micro catchments. Consequently, once the tree and grass species inside and around the micro catchments are brought about in an integrated system of land treatments may enhance infiltration and curb erosion. This may ultimately enhance biological, chemical and physical properties of the soil for fertility sustenance.

3.5 Agroforestry Systems for Increased Water Availability

Water availability is one of the most vital challenges on crop production, mainly in arid as well as semiarid climates where most smallholder farmers in Southern Africa are located. Soil degradation reduces water availability in various mechanisms, which include increasing water runoff and reducing water infiltration and water retention capacity. Through increased ground cover as well as higher SOM than monocultures, AFS minimise water runoff and soil evaporation and increase water infiltration rates and water retention capacity, availing more water for plant production across all soil layers (Siriri et al. 2013). All properly designed AFS with the capacity to curb erosion and enhancing soil organic matter will increase the water balance. Trees on contour lines aid in halting water runoff and windbreaks minimise soil evaporation through reducing wind speed. Alley-cropping systems, home gardens and tree–crop combinations all have higher rates of water infiltration as compared to monocultures due to the availability of tree litter and the utilisation of branch prunings as mulch. Tree species with low water demand should be used in AFS when water is scarce to minimise water competition between trees and crops. Minimising tree densities and making use of tree prunings will also reduce transpiration and thus tree water demand. In Malawi, the amount of water in 0–0.15 m soil profile was approximately 4–53% higher under *Faidherbia* tree canopy as compared to outside (Rhoades 1995). In a study conducted by Chirwa et al. (1994) in Zambia found higher soil water content under *Leucaena leucocephala* ((Lam.) de Wit) and *Flemingia macrophylla* ((Willd.) Merr.) hedgerows compared to the maize rows in the alleys. In Malawi, Chirwa et al. (2007) also obtained higher WUE in maize intercropped with gliricidia than in sole maize and maize intercropped with pigeonpea. In another study by Phiri et al. (2003) in eastern Zambia higher water use efficiency (WUE) was recorded in sesbania fallows as compared to continuous sole maize. In a study conducted by Musokwa et al. (2020) in South Africa, maize grown under pigeonpea fallows recorded higher WUE (11.25 kg mm⁻¹) as compared traditional continuous maize (5.42 kg mm⁻¹). Trees in AFS can remarkably impact the water availability for field crops: tree roots perforate deeper into the soil as compared to numerous field crops; as a result water infiltration rate and capacity may be increased (Rosenstock et al. 2019).

4 A Case Study of Pigeonpea-Improved Fallows at Fountain Hill Estate, Wartburg in South Africa

Pigeonpea (*Cajanus cajan* (L.) Millsp) is an important drought tolerant legume crop that can be adopted by smallholder farmers in the advent of climate change and variability (Musokwa and Mafongoya 2021). The International Maize and Wheat Improvement Center acknowledges that pigeonpea is a main contributor to food security in regions experiencing the early impacts of global climate change (Blum 2009). In RSA, pigeonpea is underutilized pulse legume crop and it is not cultivated on fields (Mulungu and Ng'ombe 2019; Oduniyi and Tekana 2019); usually, the crop is cultivated as a live fence in home gardens in Mpumalanga, Limpopo and KwaZulu-Natal provinces (Mulungu and Ng'ombe 2019). Despite a huge potential market for this crop among the Asian community in RSA, this opportunity has not been fully utilised. Roughly 120–150 tonnes are imported from Malawi every month to cater the ever-increasing demand for the dhal Indian cuisine (Musokwa et al. 2020). Improved fallows (IFs) are established when land lying fallow is planted with a fast-growing nitrogen-fixing tree species to improve soil properties (biological, chemical and physical). The trees are removed after 2 years followed by 2–3 years of cropping. IFs are a short-term substitute for the long traditional bush fallows, which are no longer feasible due to land shortage (Mafongoya et al. 2006).

Figure 1 (a and b) shows how the pigeonpea fallows were established and the removal process after 2 years.

Figure 2 (a and b) Indicates the decomposition process of leaves and twigs in pigeonpea fallows and the maize was planted after the fallow phase respectively.

Two-year pigeonpea improved fallow recorded higher soil fauna and physical soil properties as compared to traditional monocropping which normally farmers practice on degraded soils (See Table 4). In addition to higher maize yields (See Table 5).



Fig. 1 (a) Pigeonpea fallows planted at 1 m × 1 m; (b) Fallow clearing for maize planting (Photo by Misheck Musokwa)

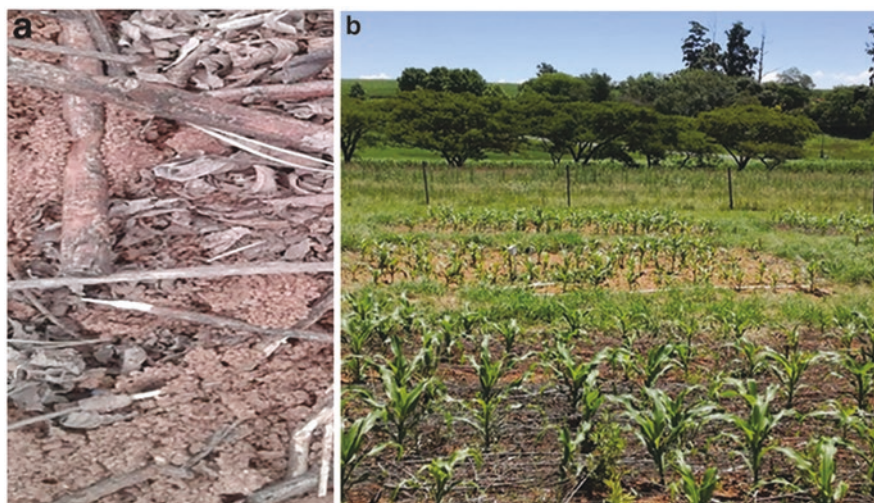


Fig 2 (a) leaves and twigs decomposing; (b) Maize planted after pigeonpea fallow. (Photo by Misheck Musokwa)

Table 4 Pigeonpea improved fallows effect on biological and physical soil properties at Fountain hill, Wartburg, South Africa (Adapted from Musokwa et al. 2020)

Farming practices	Soil macrofauna species diversity index (H')	Soil macrofauna species richness index (H')	Aggregate stability (mm)	Infiltration rate (mm/hr)	Bulk density (g/cm^3)
Continuous maize without fertiliser (traditional farming system)	0.98	6.00	5.02	12.44	1.46
Grass fallow (natural)	1.66	9.67	8.99	19.11	1.43
Agroforestry system (2-year improved pigeonpea fallow)	1.66	17.44	11.45	29.81	1.22

4.1 Lack of Policy and Institutional Support

Policies linked to land rights, labor, trade as well as taxes on agricultural commodities may have a detrimental effect on agroforestry practices or promotion (Dhyani et al. 2021; Maponya et al. 2021). Nevertheless, farmers are expected to have incentives which include free access to inputs as well farming security, regrettably corresponding organisations meant to support are not enough (Baig et al. 2021). Limited technical support, skilled personnel, demonstration sites including limited research on agroforestry systems could hamper the implementation of agroforestry systems on degraded or marginal lands.

Table 5 Effects of pigeonpea fallows on maize yields at Fountain hill, Wartburg, South Africa (Adapted from Musokwa et al. 2020)

Farming practices	Maize grain yield (kg/ha)
Maize after two-year improved pigeonpea fallow (agroforestry system)	3787
Continuous maize without fertiliser (traditional farming system)	993
Maize after grass fallow (natural fallow)	2294

4.2 The Main Benefits a Farmer Can Accrue with Improved Fallows Are as Follows:

- The time required for recovery of soil fertility chemical and biological, physical conditions are shortened compared to bush fallow, which takes about 8–10 years.
- Woody legumes can add substantial amounts of nitrogen to the soil. Some nutrients are retrieved from below the crop rooting zone and brought to the upper soil horizon and soil surface for uptake by the crop. Tree biomass addition increases SOM content and reduces leaching. The farmer saves money as there is reduction in terms of expenditure on chemical fertilisers.
- There are substantial improvements in soil properties, such as OM content, soil aggregation, and water infiltration, water holding capacity and soil moisture conditions and soil workability (making it faster and easier to plough).
- Farmers can obtain edible leaves and pods, animal and bee fodder, stakes, fuel-wood and fibre from the fallow.
- Improved fallows have the least labour demand as compared to other agroforestry soil fertility technologies.

4.3 Challenges of Improved Fallows

- Where there is a land shortage and no land left fallow, the farmer must be able to withstand the loss of crop yield during the 2 years of the improved fallow.
- The time required to cut down trees at the end of fallow can take 26 days/per person/hectare, it involves separating twigs and wood.
- Land preparation after removing the fallows is only restricted to physical or manual due to the presence of stumps in the first season. A tractor can only be used after the stumps decompose which might take longer time.

5 How the Rehabilitation of Degraded Land Could Be Successful?

Apart from committed, sustained and proactive community participation in certain project activities that focuses on rehabilitation of degraded lands other drivers of successful dry land rehabilitation programmes in denuded landscapes have been identified (Blay et al. 2004). The same author also mentioned some of solutions to make the situation successful:

1. There must be some short-term rewards or benefits, which could either be monetary or material, in addition to anticipated future beneficial impacts.
2. Local people's attitudes, behaviour and perceptions must be in line with the principle of the rehabilitation programme—the people must acknowledge as well as internalise the fact that change will be in the long-run be to their advantage.
3. Comprehensive understanding of the interconnectedness, peculiarities and complexities of dry land ecosystems, especially dry land forests and woodlands.
4. Rehabilitation must result in soil fertility enhancement, hydrological processes, etc.
5. Existing land uses must be examined, and land characteristics must be matched with land uses to establish drivers of land degradation.

6 Conclusion

Fourty years ago, AFS began to get the recognition of the scientific community international development and, fundamentally as a way of sustaining agricultural production in marginal lands. AFS revealed that all soil properties will be improved which can ultimately lead to doubling of maize yields as compared to continuous maize without fertiliser. Hence, the rehabilitated lands will help in providing SA farmers and policy makers with information on AFS (pigeonpea improved fallows) which can be adopted as an alternative sustainable way of reinstating degraded lands This can also help in lessening the burden of purchasing expensive synthetic fertilisers in rural farming communities. Smallholder farmers who have limited access to chemical fertilisers can sustainably use improved pigeonpea fallows to achieve higher yields. There is need to institute policies to scale up AFS to solve the challenges of degraded soils and reduce the burden of purchasing expensive inorganic fertilisers by smallholder farmers. AFS can improve the resilience of agricultural productions to current climate variability through use of trees for intensification and diversification and buffering of farming systems.

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Climate Change Resilient Crops to Combat Food and Nutrition Insecurity in Marginal Lands



Beverly Mampholo, Salmina Mokgehle, Nadia Alcina Araya, Meshack Mofokeng, Manaka Makgato, Neo Edwin Nyakane, Michael Bairu, Mariette Truter, Rebecca Mahlangu, Christian Philippus Du Plooy, Adornis Dakarai Nciizah, and Hintsu Tesfamichael Araya

1 Introduction

Climate change and food security are two of the world's most pressing issues, with multiple interconnected risks and uncertainties affecting food security and the livelihoods of those involved in production systems and value chains. Despite doubling food production in the last three decades, global hunger has risen since 2014 (FAO 2020), significantly impacting African countries and the rest of the world's water resources, food security, and human health. Food security refers to (i) the availability of sufficient quantities of suitable quality food, whether produced at home or imported; (ii) individual access to the resources for purchasing appropriate foods for a nutritious diet; and (iii) utilization of food through adequate diet, clean water, sanitation, and health care to reacquaint individuals with food (FAO 2006). The food system will be under additional strain as the world's population exceeds 9 billion by 2050, the food system will face increased strain. Because of the tremendous rise in global population, concurrent, strategic investments in climate-resilient

M. Bairu
M. Truter

B. Mampholo (✉) · N. A. Araya · M. Mofokeng · N. E. Nyakane · R. Mahlangu ·
C. P. Du Plooy · H. T. Araya
Agricultural Research Council, Vegetable, Industrial and Medicinal Plants, Pretoria, South
Africa
e-mail: mampholom@arc.agric.za

S. Mokgehle
School of Agricultural Sciences, University of Mpumalanga, Mbombela, South Africa

M. Makgato
Agricultural Research Council, Infruitec-Nietvoorbij, Stellenbosch, South Africa

A. D. Nciizah
Agricultural Research Council-Natural Resources and Engineering, Pretoria, South Africa

agricultural production systems, resource efficiency, low-waste supply chains, adequate nutrition, and healthy eating choices are necessary (UNPD 2011).

A prime impact of food insecurity is malnutrition, a lack of dietary energy needed to live a normal, active, and healthy life. Undernourishment happens in the form of nutritional deficiencies in vitamins (e.g., vitamin A) and minerals (e.g., iron, zinc, iodine). Recent studies based on data collected from 53 countries show that more than 27 countries reduced their calorie consumption due to climate change (Ray et al. 2019). The good news is that nutrient-rich, underutilised, neglected crops are extremely resilient to harsh environments (drought, salinity, and extreme temperature) and yield well with limited resources. This is true even though it has been anticipated that the productivity of major crops will be lower under marginal lands. (Mabhaudhi et al. 2019). According to FAO projections, most food required to feed 2 billion mouths by 2050 must come from marginal lands (FAO 2017). Many people in Sub-Saharan Africa (SSA) rely heavily on underutilised, neglected crops (leguminous, leafy, grain, root, and tuber crops) for their main source of food and nutrition. This is also due to their role in food security, owing to their ability to withstand drought in changing climates. These crops are also well known for serving as significant subsistence farming systems in SSA, where they have played a significant role in household food security and income generation owing to their ability to reach the maturity stage within a short period, which renders them very useful in supporting nutrition-intervention programmes (Mampholo et al. 2016). According to (Jaenicke and Höschle-Zeledon 2008), over 7000 underutilised, neglected crop species have been discovered and extensively used as food sources throughout human history. Underutilized, neglected crops are well positioned to offer strategic food options with the potential to improve nutrition, increase dietary diversity, and adapt to climate change, given the need for dietary variety and persistent concerns about environmental impacts. The consumption of underutilised, neglected crops significantly contributes to poverty. Future agriculture necessitates tailored solutions that integrate fundamental shifts in current knowledge and enabling technologies and consider the need to protect the environment and meet societal demands.

Climate change is a menace posing an extreme threat to the environment and human beings. Climate change is linked to rising temperatures, more intense precipitation, and changes in the interactions between crops, pests, pathogens, and weeds. It also exacerbates several trends, such as the decline of pollinating insects, growing water scarcity, rising air pollution (such as tropospheric ozone), and declining fisheries. Agriculture is the key economic enterprise at the centre of the food security dilemma because of abiotic stresses, both direct and indirect. The emission of dangerous gases, especially CO₂, is the main factor for the greenhouse effect and rising average global temperatures. The number of stress spells, their impact on everyday living, and crop damage are the primary indicators of climate change and environmental variation. Abiotic stresses, such as water scarcity and temperature extremes, significantly impact plant development and yield due to climate change. Plants are frequently subjected to various stressors in natural climate conditions, including waterlogging, drought, heat, cold, and salinity. UV-B, light intensities,

flooding, gas emissions, and physical and chemical factors that cause additional stress are all abiotic factors. A dynamic balance of suitable biophysical resources, such as soil quality, water availability, sunlight, CO₂, and temperature, ultimately determines agricultural output quantity and nutritional quality. Crop yields are extremely susceptible to temperature and water supply fluctuations and are generally coupled with high temperatures because low soil moisture decreases evaporative cooling from the landscape and because high temperatures increase crop water loss (Malhi and Kaur 2021). Climate change has detrimental effects on agriculture, particularly the produced crops.

Africa is one of the continents most at risk from persistent climate variability with strong adverse economic effects. This vulnerability is worsened by development challenges, particularly ecosystem degradation and endemic poverty, facilitated by constrained access to resources like capital, infrastructure, markets, and technology (IPCC 2007). Reduced crop productivity is the primary threat to food security, especially given the world's rapid population growth. Slow production growth and sharp annual fluctuations in output have remained chronic problems due to climate change affecting the poorest households, the most vulnerable since they devote the major share of their income to food. Hungry people are less able to concentrate and have diminished physical strength. Reduced food supply and higher prices undercut child nutrition, early childhood development, and education.

Climate change can affect prices, potentially leading to increase and greater volatility. Furthermore, increased temperatures may increase the risk of heat stress during postharvest transportation, resulting in a reduced availability of fresh products, deteriorated quality, reduced nutritional quality, and sensory appeal, as well as worsening storage conditions, which may result in reduced shelf-life. A lack of agricultural resilience to climate change critically underlies SSA food insecurity quality and distribution. Furthermore, the transition of SSA agriculture to producing crops that are more resilient to abiotic stresses like drought, heat and flooding is crucial in the face of the climate change predicted for shorter- and longer-term future by building climate resilience for food and nutrition security. Climate change is expected to have a wide range of negative effects on plant physiology, ultimately limiting plant growth, productivity, and food supply. As a result, excess food must come from marginal lands considered unsuitable for growing main staple crops under the adverse climate change scenario. Because of their high nutritional profile and improved resilience to several abiotic stresses, underutilized, neglected crops are suitable crops to improve food and nutritional security. This book chapter comprehensively reviews the multifaceted relationships between climate change and its impacts on crops, food, and nutrition insecurity, demonstrating the need for expanding populations to adjust to shifting climatic conditions (Fig. 1). Additionally, it identifies the key success factors and challenges that must be addressed to bring about the widespread use of climate change-resilient crops to combat food insecurity and ensure adequate nutrition in marginal lands. Researchers must make strategic investments at the same time to create climate-resilient agricultural production systems, effectively use resources, create low-waste supply chains.

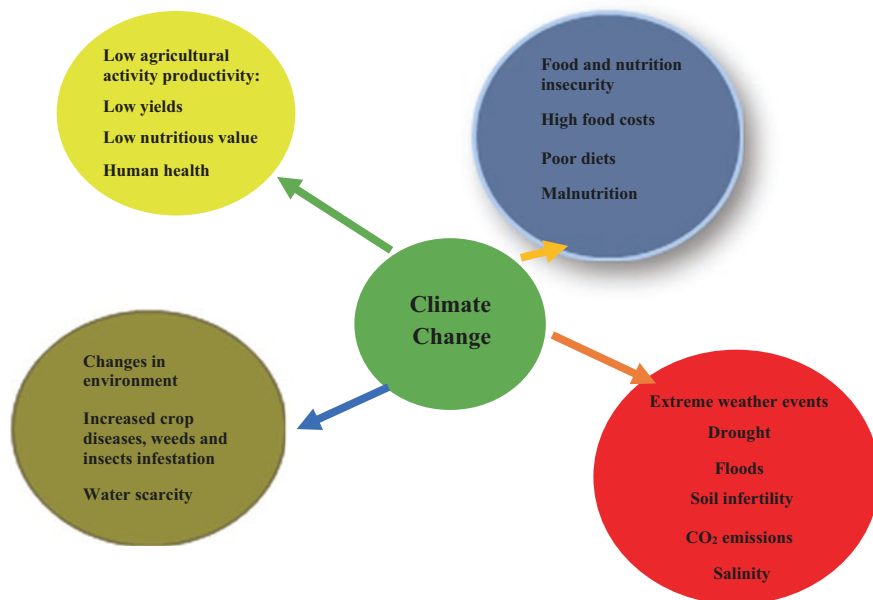


Fig. 1 Overall negative effects of climate change on agricultural production systems

2 Crop Diversity in Climate Change Adaptation

Humans have domesticated thousands of plant and animal species via deliberate selection over centuries and generated a stunning array of foods using their local biodiversity. Traditional diets have long relied heavily on gathering and hunting wild vegetables and animals (Heywood 2013). Wild, semi-wild, or domesticated plants have always been a significant source of nourishment for civilizations. According to RBG (2016), the number of plant species used for food is small, with approximately 70,000 species possessing edible parts. Despite this tremendous diversity, only three crop species (rice, wheat, and maize) produce half of the world's plant-derived calories, and 82% of agricultural land is dedicated to growing only 20 key plant commodities (Schmidt et al. 2010). Crop diversity in food systems is disappearing due to various variables, including increased production intensity and mechanization, marketing homogenization, and consumer disengagement from traditional food cultures (Koochafkan and Altieri 2017). These trends, which began with the Green Revolution and have been reinforced by agricultural market globalization, have pushed many conventional crops to the periphery of research and development. As a result, their market competitiveness has declined, and farmers have abandoned them, resulting in genetic loss (Tripp and van der Heide 1996). There are a variety of underused crops in rural regions that are used as a staple meal, a primary source of income, and medicinal herbs for treating human diseases (Van Rensburg et al. 2007) (Fig. 2). However, due to a lack of necessary expertise in their

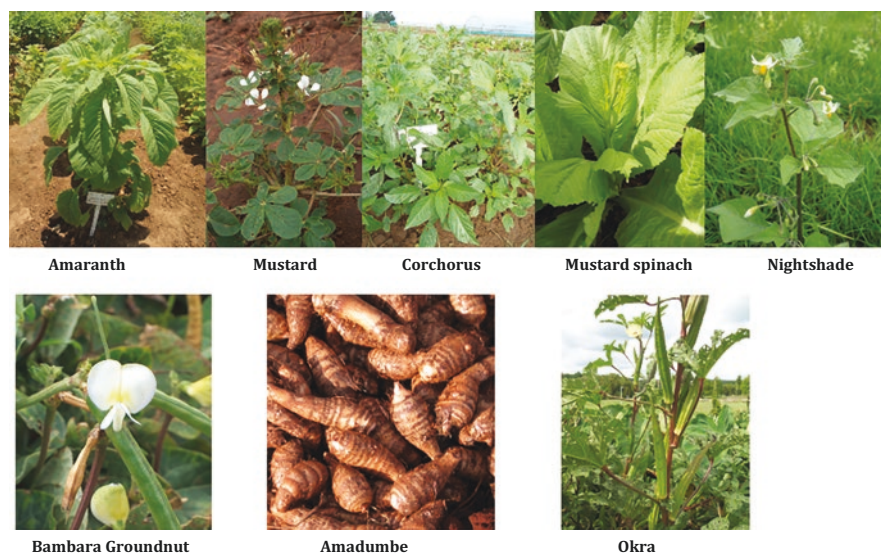


Fig. 2 Various indigenous vegetables cultivated at the Agricultural Research Council-Vegetables Industrial and Medicinal Plants, South Africa (Source: Hints Araya)

cultivation, smallholder farmers and homestead gardeners cannot produce these crops. Despite their multifaceted relevance, these crops are underutilized, and many are unaware of their significance (Luoh et al. 2014), including their potential to improve food and nutrition security in marginal lands.

Indigenous leafy vegetables are increasingly recognized as having the potential to grow in marginal lands and improve food security due to their adaptability to various environmental conditions (Mabhaudhi et al. 2019). Leafy vegetables are considered a rich source of nutrients, including pro-vitamin A, vitamin C, folic acid, riboflavin, and minerals such as iron, zinc, calcium, and magnesium needed for an adequate human diet (Mabhaudhi et al. 2019). In sub-Saharan Africa, micro and macronutrient deficiencies are a severe health problem, particularly for women and children (Galani et al. 2020). Indigenous vegetables have been an essential food source for years, providing vital nutrients and vitamins in South African rural communities. Many of these crops are not in today's formal markets as they are mostly collected from backyard gardens. Little is known about their production practices, while today's agricultural economy dictates producers to fine-tune their farming practices to maximize yields and minimize production costs. To reintroduce these crops to farming communities with cost-effective production methods, one must understand the plant with considerable precision. Several studies were conducted in two small-scale farmers' fields in South Africa to evaluate the sustainability and profitability of nutritionally important indigenous vegetable crops (Fig. 3). Several production inputs and management practices were evaluated. Results indicated that the engagement of farmers and adoption of the crops for optimizing profitability and promoting nutritious indigenous food crops was successful. Low-cost inputs such as



Fig. 3 A Farmer harvesting nutritious indigenous vegetable (*Cleome gynandra*) in South Africa (Source: Hintsu Araya)

organic fertilisers like manure improved the productivity of indigenous vegetable crops and were comparable in yield with commercial production norms. Supporting smallholder farmers to produce important nutritional indigenous vegetables could expand the diversity of our food basket; in addition to this, as most of the indigenous vegetables are wild species that could grow in harsh environments as weeds, they could bring the benefits of resilience to climate change.

3 Legumes for Food Production and Climate Change Mitigation

Legumes provide several crucial services to communities in different regions in South Africa. The root-nodule bacteria (collectively called “rhizobia”) can infect roots and form N_2 -fixing nodules in members of the Leguminosae (Pule-Meulenberg and Dakora 2009). By fixing atmospheric N_2 in symbiosis with the soil bacterium rhizobia, they can supply nitrogen (N) to agro-ecosystems, boost soil carbon content, and increase the productivity of succeeding crops. The role of legumes has hardly ever been considered in terms of their potential to help mitigate climate change by reducing the use of fossils. Ecosystems in natural and agricultural settings benefit from the mutualistic relationship between the Leguminosae and the Rhizobiaceae. Therefore, symbiotic legumes can potentially significantly increase the N economy of ecosystems. Legumes are a significant source of protein and minerals required for human and animal nutrition and contribute to soil N development. Therefore, symbiotic N_2 fixation by rhizobia offers a more affordable, environmentally friendly, and sustainable nitrogen source for resource-poor farmers in developing countries.

Given the broad distribution of N₂-fixing Leguminosae in Africa, biological N₂ fixation must be the main route for N intake into that region's desert and natural ecosystems. In Africa, food legumes such as cowpea (*Vigna unguiculata* L. Walp.), groundnut (*Arachis hypogaea* L.), soybean (*Glycine max* Merrill), common bean (*Phaseolus vulgaris* L.), and Bambara groundnut (*Vigna subterranean* L. Verdc.) form a major integral part of the traditional cropping system, and thus, offer a great opportunity for increasing N supply for resource-poor farmers (Hirsch et al. 2003). These grain legumes improve soil N fertility and benefit intercrops or succeeding cereal crops (Dakora and Keya 1997; Hardarson and Atkins 2003; Herridge et al. 2008). The most widely cultivated edible legumes in various parts of Africa include cowpea, Bambara groundnut, and groundnut, presumably due to their relative adaptability to this environment of frequent drought and low nutrient availability. Studies have demonstrated the beneficial impacts of fixed-N from symbiotic legumes on cereal crops like sorghum, whether in rotation or as an intercrop.

Numerous limitations, such as high soil temperatures, low levels of mineral nutrients, and low soil pH, limit research on biological nitrogen fixation in various parts of Africa and South Africa (Pule-Meulenberg 2014). Estimates of N₂ fixation in laboratory settings demonstrate that grain legumes can give a sizable quantity of nitrogen to the continent of Africa's conventional cropping systems (Mokgehele et al. 2014; Pule-Meulenberg and Dakora 2009; Belane and Dakora 2009). Several research studies have utilized various methods to assess the symbiotic N₂ fixation by groundnuts under experimental circumstances in Africa, and the results have been highly variable. For instance, Gathumbi et al. (2002), observed that groundnut production in Kenya averaged 8 kg N. ha⁻¹. According to Sanginga (2003), the amount of nitrogen fixed by groundnuts varied between 11 and 63 kg.ha⁻¹ in Nigeria and 19 to 79 kg.ha⁻¹ in Zambia. Several biotic and abiotic factors, including the quantification method, genotypes examined, the number of reference plants used, and others, could all contribute to the difference in the amounts of N this legume contributed. Due to its significant N contribution to soil fertility, other legume crops, such as groundnut, have an advantage over grain legumes like a common bean (*Phaseolus vulgaris* L.) as an N₂-fixing crop.

Most legume crops encourage using high-intensity cropping systems, including intercropping, which, depending on the situation, might be a practical way to boost agricultural productivity and production overall (Maitra et al. 2020). Intercropping gives farmers access to a greater range of crops to harvest, which helps farmers fight food and nutrition poverty and diversify household food baskets. Intercropping is growing two or more crops concurrently on the same field for sufficient time to cover the vegetative stage (Bele et al. 2014; Gebru 2015). Intercropping is connected to agricultural techniques like double cropping and mixed cropping, which allow for more effective use of resources on the farm and sustainable crop output (Maitra et al. 2020; Li et al. 2020). Figure 4 illustrates intercropping a leguminous crop (cowpea: *Vigna unguiculata*) with a cereal crop (maize: *Zea mays*). Cowpea can offer affordable symbiotic nitrogen as a biofertilizer to improve soil fertility in cropping systems, just like most N₂-fixing legumes. Implementing sustainable methods like intercropping is necessary to boost agricultural output and increase



Fig. 4 Cowpea (*Vigna unguiculata*) and Moringa (*Moringa oleifera*) intercropped at the Agricultural Research Council—Vegetable, Industrial and Medicinal Plants field site (Source: Hintsa Araya)

resource use efficiency due to the changing climate (temperature, rainfall, etc.) (Gebre 2015; Khanal et al. 2021).

4 The Resilience of Non-Leguminous Crops to Climate Change

Non-leguminous cover crops can improve soil organic matter by increasing biomass production and scavenging nutrients, particularly N, left behind from earlier crops (Singh et al. 2020). It has also been noted that non-leguminous cover crops can lower nitrate leaching losses (Nouri et al. 2022). Non-leguminous cover crops have become more important since their crop residues in conventional systems are insufficient to compensate for the loss of soil organic matter caused by high mineralization rates. Furthermore, non-leguminous cover crops could supplement the scarce supply of farmyard manures by being sown before cereal crops like maize (*Zea mays*). Pearl millet (*Pennisetum glaucum* L.), fodder maize, and sorghum (*Sorghum bicolor* L.) are a few of the common non-leguminous cover crops (Singh et al. 2020). Cutting crops before planting subsequent maize has been reported to benefit non-leguminous cover crops as fodder crops. While research has demonstrated the importance of flower removal on non-leguminous crops, their effects on yield and quality have not been researched extensively.

4.1 *Non-Food Crops Contribution to Combat Food Insecurity*

A crop grown for industrial purposes only, as opposed to producing food for human consumption, is referred to as a non-food crop or industrial crop. Non-food crops include crops such as cotton (*Gossypium hirsutum*), jute (*Corchorus capsularis*), sisal (*Agave sisalana*), and flax (*Linum usitatissimum*) (Heidari et al. 2021). Non-food crop products promote their increased usage as industrial raw materials, for instance, through fostering collaborative efforts between researchers and the agriculture sector. Non-food crops are employed as industrial raw materials for various reasons, including their capacity to provide higher technical performance or a more economical raw material and their frequent ability to promote sustainability and the environment. Cotton production in South Africa is associated with weaving yarns (used for towels, denim, and sheets) and knitting yarns (e.g., fabrics and underwear). Some major cotton products associated with cotton from the seeds include oil, soaps, and hulls (Bennett 2001). Some non-food crops, such as cotton, have high-value, low-volume ones used in pharmaceuticals where supply quality and traceability are crucial and can be produced profitably without government assistance. Jute (*Corchorus capsularis*) has different parts used as medicine to treat many ailments in different regions of the world (Biswas et al. 2022). For example, in South Africa, the leaves treat gonorrhoea, tumours, and aches and pains (Mahwasane et al. 2013). Jute production in some countries, such as India and China, is associated with fibre (Saleem et al. 2020). The previous research on jute also described the characteristics of lignin and carbohydrates. Despite the contribution of the previous studies on jute, there is still a need to maximize the exploitation of fibre to have a complete understanding of the crop's composition. Standards can ensure bio-based goods achieve a quality equivalent to or better than requiring a minimum proportion of renewable content or encourage non-food uses of crops more easily met by natural products than competitors. In terms of sisal, products such as plastic and rubber can be produced from the plant due to its potential as reinforcement in polymer composites due to its low density.

4.2 *Agro-Ecological Approaches to Climate Change*

Improving crop productivity, even in marginal lands, is the main aim of agricultural production. Ecological-based alternatives combining multiple components in one system may provide a robust path to increase agricultural productivity, sustainability, and resilience (Burgess et al. 2022). Conventional farming has detrimental effects on the environment due to the excessive use of fertilizer, which degrades water and soil quality and disrupts the global nitrogen cycle by promoting the emission of reactive nitrogen gases into the atmosphere (Fung et al. 2019). The effects on the environment include detrimental declines in forest area. For example, 53% of the total land in the Philippines is classified as forest lands; however, only 19% is

adequately covered with forest vegetation due to the destructive conversion of forest land to permanent annual cropping areas (Magcale-Macandog et al. 2010). This has ultimately led to alarming declines in land productivity as it resulted in massive soil degradation or erosion (Magcale-Macandog et al. 2010). In India, approximately 120.8 million ha of previously arable- and forest land is declared degraded (Sarvade and Singh 2014). Agriculture must sustainably contribute to food and nutrition security and the rural economy while reducing the negative impacts on or improving the environment (Chimonyo et al. 2020).

4.3 Agroforestry as an Approach to Climate Change

Agroforestry addresses issues of ecological and economic strategies for climate change adaptation and mitigation (Newaj et al. 2013). The increase in food shortage due to reduced productivity caused by land degradation and climate change has increased interest in agroforestry to improve soil conditions and enhance local climate conditions (Mbow et al. 2014). Agroforestry is a system where woody perennial trees are used in the same land-management unit with crops and animals for ecological and economic benefits (Everson et al. 2011; Maponya et al. 2021). The interaction between trees and other components of agriculture may be important at various scales, such as at a field scale where trees and crops are grown together, at a farm level where trees may provide fodder for livestock, and at a landscape level where the system is used for ecosystem services (Coulibaly et al. 2017). One of the ecosystem services may be a scenario where tree canopies and leaf litter protect the soil against erosion and high temperatures (Alfaia et al. 2004). In the apiculture system, pollination is an important ecosystem service as it positively impacts biodiversity and food production (Etxegarai-Legarreta and Sanchez-Famoso 2022) (Table 1).

Table 1 Various agroforestry systems used around the world

Land use system	Description	Reference
Agrisilviculture	Integration of trees with other woody perennial	Sarvade and Singh (2014)
Agrosilviculture		Uleh and Usman (2020)
Agrisilvipasture	Combining trees with crops and livestock	Sarvade and Singh (2014)
Agrosilvipastoral		Tolunay et al. (2007)
Silvopastoral	Combining trees with pasture and livestock	Sarvade and Singh (2014)
		Dwivedi et al. (2007)
Agrihorticulture	Integration of fruit trees with crops	Sarvade and Singh (2014)
Apiculture	Integration of trees with honey bee-keeping	Sarvade and Singh (2014)
		Tolunay et al. (2007)
Aqua forestry	Includes cultivation of aquatic plants or production of fish in water bodies within tree forests	Sarvade and Singh (2014)
		Tolunay et al. (2007)

Agricultural land faces several environmental threats, such as land degradation by erosion, invasive alien species and overgrazing (Zerihun 2020). Agroforestry is a potential tool for managing harsh environments, creating favourable microclimate conditions, improving soil health, and conserving biodiversity (Newaj et al. 2013). Agroforestry-based adaptation to climate change is based on reversing negative trends in diverse tree cover and a targeted shift in resource capture to adjust to the changing climatic conditions (Van Noordwijk et al. 2021). Everson et al. (2011) mentioned that an improvement in the efficiency of land use systems is required to maximize the use of scarce resources, such as water, to increase productivity and minimize resource degradation. Climate change mitigation strategies, in most cases, focus on reforestation and forest protection and conflict with the need to expand agricultural production to meet the growing food demand (Mbow et al. 2014). However, agroforestry can provide a good strategy to address forest protection and food security needs. For example, a study in Tanzania indicated that farmers were growing tree species used for food (*Cocos nucifera*), fruits (*Mangifera indica*, *Persea americana*), timber production (*Tectona grandis*), shading (*Ficus stuhlmannii*), and other trees for animal fodder (Nnko et al. 2022). Land-based economic development strategies, including agroforestry, are major in livelihood improvement and economic development (Zerihun 2020). In a study by Maponya et al. (2021), rural community members reported increased food access and reduced food insecurity due to the agroforestry project they were involved in.

Magcale-Macandog et al. (2010) reported that agroforestry increased farm benefits by 42–137%, while during the same period, farmers practicing monoculture incurred losses in the Philippines. One farmer in India increased farm total return by 16.5–136.2% through agri-horticulture, compared to monoculture (Dwivedi et al. 2007). Growing annual crops such as corn in combination with fruit trees increased household food security, and corn yield increased annually under agroforestry compared to monoculture, where there was a gradual decline in corn yield in 9 years (Magcale-Macandog et al. 2010). Apiculture provides farmers with innovative new products with economic and income generation opportunities, thus improving their economic food access and security (Etxegarai-Legarreta and Sanchez-Famoso 2022). Devkota et al. (2016) found that apiculture had a higher benefit-cost ratio and provided higher opportunities for farmers to earn a better living by earning additional revenue from selling bee products.

Agroforestry can improve soil fertility by increasing the soil organic matter content and N₂ fixation, especially by leguminous trees, facilitating nutrient cycling, improving the soil structural properties, and conserving soil moisture (Mbow et al. 2014). Trees contribute to more efficient nutrient cycling and prevent nutrient losses due to leaching, as they have a dense, deep and permanent network of roots (Alfaia et al. 2004). Leguminous trees can contribute to the supply of N into the soil by fixing atmospheric N into the soil (Coulibaly et al. 2017). In a bamboo-maize, bamboo-cassava, and bamboo-cowpea agroforestry study, soil moisture and cation-exchange capacity were significantly improved in year three (Akoto et al. 2020). Atapattu et al. (2017) studied the effects of eight forest plant species on soil physical properties under agroforestry and reported significant increases in soil organic matter,

exchangeable potassium, and total nitrogen concentration in leguminous tree species. The soil microbial activity was also improved in the agroforestry system (Atapattu et al. 2017). Zakes et al. (2015) studied a banana-coffee agroforestry system and reported that the system significantly increased total soil organic matter and N compared to banana mono-cropping, and total C was increased by 26%.

4.4 Intercropping for Improved Crop Variety

Intercropping is the cultivation of two or more crop species, or genotypes, simultaneously to maximize productivity per land area using a few resources (Burgess et al. 2022; Hinamen et al. 2016). The benefits of intercropping include maintaining and improving soil quality and fertility, reduced pathogen and insect infestation levels, reduced need for nitrogen fertilizers where nitrogen-fixing species are used as intercrops, increased profit margins, and reduced input costs (Hinamen et al. 2016). With appropriate management practices, Chimonyo et al. (2020) concluded that intercropping maize and Bambara groundnut can adapt when water resource decreases are projected. Intercropping can also improve land-use efficiency, where fewer land areas are required to improve yield (Fung et al. 2019).

Energy yield was calculated by Sun et al. (2020) to determine the yield advantage of a maize-based intercropping system, and it was reported that the system increased the energy yield compared to the sole cropping system. The study further reported an increase in the maize-based intercropping system's economic benefit (input-output evaluation) (Sun et al. 2020). Fung et al. (2019) found that maize-soybean intercropping reduced the nitrogen need of maize by 33%, producing the same maize yield compared to the sole maize system, in addition to the soybean yield.

Intercropping of maize and potatoes resulted in reduced yield of both crops when assessed individually and compared with sole cropping; however, a combined yield of one row of maize and two rows resulted in an increased total land yield (Kidane et al. 2017). Intercropping can increase the availability of a variety of food for nutrition purposes. Intercropping of cotton and peanuts with various plant populations increased field utilization efficiency and a significant increase in net profits, 127.8% higher than cotton monoculture (Wang et al. 2022).

4.5 Crop Rotation as a Sustainable Strategy for Resilience

Crop rotation is the recurrent succession of crops on the same land in consecutive seasons, and this method suggests that crops generally follow a pre-determined order, and this is a farmer's decision on what type of crops to grow in the current and coming growing seasons (Barbieri et al. 2017; Chongtham et al. 2017). Considering the history of agriculture, crop rotation has emerged as one of the first

sustainable agricultural practices, which improved yields by taking advantage of niche complementarity, optimising nutrient use, and reducing pests and pathogen loads (Dias et al. 2015).

Crop rotation is frequently used as an alternative technique to combat the harmful side effects of intense cropping (Xuan et al. 2012). Compared to conventional farming, crop rotation is particularly important in organic farming because of the restrictions on using easily soluble mineral fertilisers and the prohibition of synthetic chemicals to control weeds, pests, and diseases (Chongtham et al. 2017). Crop rotation can bring agronomic benefits in conservation agriculture and, in addition to economic gains, bypassing edaphoclimatic difficulties in the region (Volsi et al. 2020). According to Shah et al. (2021), crop rotations with various crops benefit the farmers, reduce production risk and uncertainty, and enhance soil and ecological sustainability.

4.6 Mixed Farming to Increase Food Production

Mixed farming is one of the basic agricultural modes that appeared during the middle and late Peiligang Culture and became a common subsistence economy at the end of the Neolithic (YuZhang et al. 2016). In order to ensure sustainable agriculture, Mekuria and Mekonnen (2018) define mixed farming as the simultaneous production of crops and livestock rearing. This type of enterprise balances and integrates crop and livestock enterprises to spread economic risk and capture synergies in terms of forage supply, but in many parts of the world, these have become increasingly separated and specialized (Bell et al. 2015).

Mixed crop-livestock systems are the predominant farming system throughout the semi-arid and sub-humid zones, with important contributions to meat and milk production, to crop productivity through the provision of manure, and to livelihoods for millions of rural people (Descheemaeker et al. 2018). This farming system is important as it accounts for almost half of world food production and is present in all edaphoclimatic areas. In addition, it provides sound alternatives to progressively achieve world food production by sufficiently utilizing available natural resources. Agriculture is supported by a substantial role and the prevalence of mixed agricultural systems, particularly in the humid tropics (Stark et al. 2018).

4.7 Drought-Tolerant and Water-Efficient Crops

According to Shanker et al. (2022), “drought-tolerant crops” are cultivars of plant species with coping mechanisms that allow them to escape, avoid, or survive drought stress. Developing drought-tolerant crops for improved water utilization in agriculture is one of the most important areas of plant breeding. The agricultural industry consumes the most water globally, and as a result, in arid areas—which include

many developing nations—the amount of water used for crop cultivation might surpass 90% of total consumption (ISAAA 2022). Selecting or developing drought-resistant crops becomes crucial to tackle this challenge, particularly in water-scarce environments. Such crops have particular morpho-physio-anatomical characteristics, including, but not limited to (1) early stomata closure; (2) increased photosynthetic efficiency; (3) low cuticular transpiration rate; (4) deposits of lipid layers; (5) reduced leaf area; (6) waxy leaf area; (7) higher number of stomata found at a lower leaf surface and located in deep cavities or depressions of leaf tissues and (8) efficient water uptake and transport mechanisms (Ortiz et al. 2019). Modi and Mabhaudhi (2013) listed several underutilised, neglected crops in South Africa which possess such drought-tolerance characteristics, namely amaranth, Bambara, cowpea, maize landraces, pearl millet, taro, wild mustard and wild watermelon. The drought tolerance of these crops was evaluated by testing their response to different planting periods (early—August to September mid -mid-October to November, or late season planting—January to February) or soil water supply regimes (irrigated and rainfed cultivation). The study demonstrated that maize requires sufficient water supply for increased productivity and, as a result, it may be less drought-tolerant than other traditional crops investigated concurrently. Wild watermelon, on the other hand, performed the best with early planting, suggesting that the crop is tolerant to water stress during the early vegetative stages, making it suitable for early planting and possibly obtaining high yields. Cowpea and amaranth demonstrated superior performance under relatively low soil water supply, while taro and Bambara groundnut were quite sensitive to water stress. Modi and Mabhaudhi (2013) investigated the water use and water use efficiency of amaranth, taro, and Bambara groundnut. The highest water use efficiency of Amaranth was observed under the least irrigation water regime (up to 30 kg m^{-3}), taro under 60% actual evapotranspiration (up to 0.49 kg m^{-3}), while Bambara groundnut under 30% actual evapotranspiration (up to 0.262 kg m^{-3}). However, taro and Bambara groundnut yield were significantly compromised with reduced water supply, which shows that these crops are better cultivated under limited to non-existent water stress conditions.

4.8 Effect of Climate Change and Soil Salinity

Soil salinization has become one of the world's most severe environmental and socioeconomic problems, and it is expected to worsen due to climate change. Climate trends affect the salinization process. According to the Soil Science Society of America, saline soil is a non-sodic soil with enough soluble salt to harm most horticultural crops (SSSA 2008). Soil salinization is a land degradation process that causes an excessive buildup of soluble salts in the soil. Low rainfall, native rock weathering, sea level rise, and poor farming methods, such as irrigation with extremely salinized water, are all factors that contribute to soil salinization. (Bleam 2016).

Climate change and increasing temperatures are fundamentally the reason for soil salinization (Hassani et al. 2021). Changes in rainfall caused by global climate change may impact surface moisture availability, which is critical for germination and crop stand establishment in rainfed regions. Salinity slows the germination rate and, at higher levels, reduces germination percentage. At low concentrations, the only effect is on the germination rate, not the total percentage of seeds germinated. Microbes have also surfaced as significant contributors. As the primary intermediates of carbon turnover in the soil, they consume glasshouse gases (Patil and Lamnganbi 2018). Increased soil temperature results from increased air temperature, accelerating diffusion-controlled reactions and solutions chemical reaction rate. Typically, salinity is determined by averaging the electrical conductivity of a saturated soil paste extract collected from the plant's root zone over time and depth (Spiteri and Sacco 2024). Different values of EC, varying from 2 dS m⁻¹ to even 30 dS m⁻¹, are used as the minimum salinity threshold for characterizing the saline soils, depending on the soil classification scheme.

Soil salinity in the root zone can occur due to decreased water availability in irrigated farming regions, upward movement of salts from shallow water tables, reuse of degraded water, and salt-water intrusion. The development of salinity in the root zone can increase nitrogen leaching from the soil and decrease crop yields. Under salt duress, plant biomass, leaf area, and development have all decreased. Salt buildup in the root zone causes osmotic stress and breaks cell ion homeostasis by inhibiting the uptake of elements such as K⁺, Ca²⁺, and NO₃ and causing the accumulation of Na⁺ and Cl. (Paranychianakis and Chartzoulakis 2005).

Salinity will impact 50% of the world's arable land by 2050. Soil salinity reduces the yield of many agricultural goods, including most vegetable harvests. However, a global concern is a substantial increase in yield and consumption of vegetable crops comprising edible portions of herbaceous species (roots, tubers, shoots, stems, leaves, fruits, and flowers). In reality, fruits and vegetables are critical to our everyday survival. There are undeniable health advantages to eating a variety of fruits and vegetables. This is mainly because fruits and vegetables are high in antioxidants. Phytochemicals found in these vegetables include vitamin C, thiamine, niacin, pyridoxine, folic acid, minerals, and nutritional fibre. A lack of vegetables has been related to some of the world's most prevalent and debilitating nutritional diseases, such as micronutrient deficiencies.

4.9 Climate Change, Food Production and Postharvest Technologies to Combat Food Insecurity

All sustainable agriculture growth programmes include research and investment components to reduce waste. Postharvest food wastage is known as “food losses” or “spoilage.” Food loss is a decline in quantity or quality that renders it unfit for human consumption. (Parfitt et al. 2010). According to the FAO, UNICEF, WFP,

WHO (2012), one-third of all food produced for human use is lost or discarded and ends up in landfills. Global losses in the food supply chain are expected to be around 1.3 billion tonnes per year along the food supply chain, with Sub-Saharan Africa accounting for 230 million tonnes per year. Fruits and vegetables account for most food losses. (FAO, UNICEF, WFP, WHO 2012). Understanding the causes of food loss and waste is a critical step towards increasing resource efficiency and, in the long run, contributing to the achievement of the three Sustainable Development Goals: Goal 2 is to end hunger; Goal 12 is to promote sustainable usage and production; and Goal 13 is to combat climate change.

Food waste also involves wasting the water and energy used to grow, harvest, transport, and package it. Methane, a greenhouse gas even more potent than carbon dioxide, is released when food rots in a landfill. Food loss and waste negatively impact the environment and speed up climate change. Additionally, it states that the agri-food sector is responsible for around 31% of all greenhouse gas emissions contributing to global warming (FAO 2019). Methane emissions may drop by 45% by 2030 if food loss and waste are reduced. Methane, it is noted, has an initial 20-year warming potential that is more than 80 times greater than that of carbon dioxide. It claims that human activity is to blame for at least 25% of the methane-related global heat we are currently experiencing (Shivanna 2022).

Moreover, methane primarily contributes to ground-level ozone (tropospheric O_3) formation, a hazardous air pollutant and greenhouse gas directly harmful to human health (Fig. 5). Tropospheric O_3 is a secondary air pollutant associated with adverse health effects, including asthma, reduced lung function and chronic obstructive pulmonary disease. According to Huangfu and Atkinson (2020), short- and long-term exposures are linked to detrimental health effects and early mortality. Methane also harms plants by causing cellular damage within the leaves, adversely affecting plant production, reducing the rate of photosynthesis, and requiring increased resource allocation to detoxify and repair leaves (Ashmore 2005; Sitch et al. 2007).

Food waste and loss can be decreased by implementing low-cost postharvest technology, such as improving cold chains, educating consumers, and donating



Fig. 5 Measures to prevent and reduce food waste and formation of methane greenhouse gas-emission (Image: Beverly Mampholo)

excess food. Postharvest technology involves all treatments or processes that occur from the time of harvesting until the foodstuff reaches the final consumer. Efficient harvesting, carrying, transportation, handling, storage, processing, preservation, packaging, marketing, and utilization techniques. According to Garcia-Benitez et al. (2020), handling procedures, including harvesting, pre-cooling, cleaning and disinfecting, sorting and grading, packaging, storage, and shipping, were crucial to maintaining quality and increasing shelf life. The efforts to prevent vegetable and fruit losses between harvesting and consumption are meagre. Several factors influence the postharvest losses of vegetables. The losses due to physical, physiological, mechanical, and microbial conditions are characterized by high metabolic activities (Mampholo et al. 2015). With a loss of about 10–15% in fresh weight, vegetables appear shrivelled and stale, considerably lowering their market value and consumer acceptability (Yahaya and Mardiyya 2019). Fruits and vegetables are perishable crops with a limited shelf life of about 48 h in tropical climates due to their high moisture content. Postharvest handling practices are needed to extend the crop's shelf life after harvest. Failure to adhere to handling practices can result in a high loss (Mampholo et al. 2015). It is, therefore, important to know the appropriate handling practices and treatment methods needed for harvested vegetables to reduce postharvest losses, thereby increasing profitability for handlers in developing countries (Arah et al. 2016).

Packaging is a food container that guards against mechanical harm and maintains sanitation. It also serves as a practical instrument for extending storage life and keeping bioactive ingredients and volatile molecules linked to flavor (Chandra et al. 2018). Packaging decreases post-harvest losses, which increases food availability for the expanding human population, lowers the production area needed, and protects natural resources. Utilizing genotypes with a longer postharvest life, an integrated crop management system that results in good keeping quality, and proper postharvest handling procedures that protect the quality of the goods are all examples of loss prevention strategies. Consumers desire fruit and vegetables with good flavour and nutritional quality and ornamentals with attractive appearances and long post-production life (Kader 2003). Strategies for delaying the browning and softening of wounded plant tissues and for maintaining their safety by minimizing microbial growth have been developed (Lamikanra 2002), but more research is needed to enable the extension of post-cutting life based on flavour and nutritional quality (Kader 2003).

Packaging separates the product from its surroundings and works to maintain conditions that, if not sterile, at least minimize exposure to pollutants and pathogens, hence extending the shelf life of goods (Hailu et al. 2014). Packaging effectively prevents water loss; however, it also modifies the packaging atmosphere. If the storage temperature cannot be kept low, high oxygen transmission rate (OTR) is recommended, as too low permeability causes quality loss due to anaerobic respiration (Lokke 2012). Packaging fresh produce in polyethylene bags has become a common practice nowadays. According to Hailu et al. (2014), packaging alters the composition of the air to provide the ideal environment for preserving the produce's quality. By decreasing respiration rate, enhancing moisture retention, and

preventing physiological deterioration, a modified environment produced by packaging increases the storage life of produce (Sharma et al. 2018).

Packaged and marketed in plastic bags or films is to reduce water loss, with any atmospheric modification of O_2 , CO_2 and C_2H_4 concentrations being incidental. Modified atmosphere packaging is very effective in retaining freshness and extending the shelf life of fresh produce by maintaining the colour, inhibiting water loss, reducing loss due to product respiratory heat, and maintaining the natural fresh taste of produce (Caleb et al. 2013). Storage circumstances influence leafy vegetables' physiological and visual quality from harvest to consumption. Low temperature is an important element in quality maintenance because it reduces respiration, reduces overall metabolism, and extends shelf life. (Spadafora et al. 2016). Good harvesting techniques can decrease mechanical damage and following waste due to microbial attack. (Wills et al. 1989). Food loss levels for a particular crop vary at various stages of the postharvest system. Even losses at a particular stage of the crop in the postharvest system may vary across nations, depending on climate and postharvest methods used.

5 Conclusion

Rising temperatures and an increase in the frequency of heat waves, droughts, and heavy downpours demonstrate that climate change is no longer a mirage but a reality. Rising poverty and food insecurity levels have also revealed the absence of social safety nets. However, underutilised crops are commonly considered future crops because of their ability to withstand extreme weather conditions, and they can be a valuable resource for tackling climate change, food and nutrition security, and food and nutrition security. Therefore, there is an urgent need to broaden the food basket of Sub-Saharan Africa by revisiting the cultivation of underutilised, neglected food crops and adapting to climate change. Despite being neglected, there is proof that these resilient crops can better adapt to extreme climatic conditions and are more resistant to abiotic stresses. Adaptation measures will aid in improving food security to climate change and allow them to generate more harvestable yields in marginal soils. Future perspectives on understanding population size trends are critical to estimating future food demands. Climate change has complicated and still-evolving effects on food systems. Agriculture is a sensitive sector that relies heavily on land, water, and other natural resources that climate affects. Access to safe and nourishing food is a fundamental human need, and food systems must be designed with this in mind. To adapt, it will be necessary to set up water conservation measures, employ water-use efficiency strategies to deal with higher temperatures and alter production methods where significant climate change will make it impossible to grow certain crops.

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Part II
Reclamation and Management of Marginal
Soils

Strengthening Crop Production in Marginal Lands Through Conservation Agriculture: Insights from Sub-Saharan Africa Research



P. Nyambo, M. E. Malobane, Adornis Dakarai Nciizah, and H. A. Mupambwa

1 Introduction

Agriculture has become imperative for economic growth, poverty reduction and food security in Sub-Saharan Africa (SSA) (OECD/FAO 2016; Bjornlund et al. 2022). The agricultural sector's contribution to SSA's gross domestic product (GDP) was 17.2% in 2021, down from 18.4% in 2020 (World Bank 2023). Achieving the Sustainable Development Goals, which include zero hunger and no poverty among other in SSA, will largely depend on increasing agricultural productivity and trade, particularly among smallholder farmers. However, productivity among these smallholder farmers has largely remained low due to several factors, such as the over-reliance on rainfed agriculture, climate change and farming on marginal lands with low soil quality and limited access to water (Nyambo et al. 2020a). It is difficult to sustain crop production under these low-quality marginal soils, where most of the Sub-Saharan African smallholder farmers are located (Malobane et al. 2018). To mitigate the challenge of poor soil quality, researchers have advocated for

P. Nyambo (✉)

Risk and Vulnerability Science Centre, University of Fort Hare, Alice, South Africa

M. E. Malobane

University of South Africa, Department of Agriculture and Animal Health,
Florida, South Africa

A. D. Nciizah

University of South Africa, Department of Agriculture and Animal Health,
Florida, South Africa

Agricultural Research Council – Natural Resources and Engineering, Arcadia,
Pretoria, South Africa

H. A. Mupambwa

Sam Nujoma Marine and Coastal Resources Research Center, Sam Nujoma Campus,
University of Namibia, Henties Bay, Namibia

conservation agriculture (CA) as a sustainable solution to improve soil quality and thus improve crop productivity in SSA's marginal lands (Thierfelder et al. 2017; Corbeels et al. 2015). Despite the reported advantages of CA, its adoption among smallholder farmers largely remains very low (Nyambo et al. 2022), raising questions about its functionality within smallholder farming systems (Brown et al. 2018). Smallholder farming systems are quite complex as they involve inter-dependent mixtures of crop and animal farming, and as outlined by Stevenson et al. (2014), there are sound agronomic and social reasons why smallholder farmers tend not to adopt CA, and this is mainly because the components of CA might not be consistent with the objectives of the smallholder farming systems. In order to provide insights into the possibilities for enhancing crop production in marginal lands and improving the adoption of CA, it is necessary to analyse the experiences and results from local research studies carried out in the SSA context.

Utilising crop rotation or diversification, maintaining soil cover, and limiting soil disturbance are the three primary pillars of CA (FAO 2013). Smallholder farmers can reduce soil erosion, maintain soil structure, and save moisture in areas with limited water resources by using reduced tillage or no-till techniques (Njaimwe et al. 2016). Furthermore, preserving soil cover through strategies like mulching or cover cropping guards against soil deterioration lowers weed development, and improves nutrient cycling (Nyambo et al. 2021; Swanepoel et al. 2018). Crop variety and rotation enhance soil health, disrupt insect life cycles, and boost overall output. These ideas work together to create resilient and sustainable agricultural systems that increase yields, save resources, and reduce adverse environmental effects (Nciizah et al. 2021). However, there are also critics of CA, as highlighted in a review by Giller et al. (2009). Its drawbacks are caused by the diversity, resource disparities, and socioeconomic complexity of the area, others indicate that the benefits are site-specific, thus explaining its low adoption. Giller et al. (2009) further concluded that CA can not be considered as a panacea from the critical problems being experiences in SSA and there is no case of promoting it.

Various research studies in SSA investigated the effectiveness of CA methods in enhancing productivity on marginal lands (Malobane et al. 2018). These studies have explored a range of crop and soil parameters, including chemical properties (Mhlanga et al. 2022; Gura and Mnkeni 2019; Nyambo et al. 2021), physical (Eze et al. 2020; Nebo et al. 2020; Sithole et al. 2016) and biological properties (Coulibaly et al. 2022; Gura et al. 2022; Mhlanga et al. 2022), greenhouse gases (Nyambo et al. 2020b; Thierfelder et al. 2017), yield (Galani et al. 2022a; Nyambo et al. 2020a) and socio-economic implications of adopting CA (Ngaiwi et al. 2023; Omulo et al. 2022). By drawing on local expertise, these studies have provided valuable insights into the practical challenges, benefits, and adaptations required to successfully implement CA practices in the SSA region.

The experiences and conclusions from local research projects that illustrate the potential of CA in enhancing crop and soil productivity in marginal lands in Sub-Saharan Africa will be covered in this chapter. Case studies, empirical research, and field observations will be examined to comprehend CA's effects on diverse crops, farming systems, and local populations. This chapter attempts to assess the

potential, constraints, and suggestions for developing CA in marginal areas throughout Sub-Saharan Africa by synthesising the existing research. Understanding the experiences and ideas acquired through local research in SSA is critical for policymakers, agricultural practitioners, and development organisations aiming to promote sustainable farming practices on marginal lands. By leveraging the knowledge generated by these studies, stakeholders can develop effective strategies, tailor interventions, and provide the necessary support to farmers, ultimately contributing to the goal of strengthening crop production and improving livelihoods in SSA marginal lands.

2 Conservation Agriculture

FAO (2008) defined CA as a farming system that enhances biodiversity and natural biological processes above and below the ground surface. This is achieved through three key principles: minimum soil disturbance, permanent soil cover maintenance, and plant species diversification. By implementing CA, farmers can experience increased water and nutrient use efficiency on their soils, leading to improved and sustained crop production. As a result, revered international organizations such as FAO and World Bank and regional bodies like the New Partnership for Africa's Development (NEPAD) have actively promoted CA as a highly effective approach for building resilience to climate change.

Conservation agriculture builds the resilience of soils to climate change through the improvement of soil organic matter input into the soil, improved biodiversity and fertility. Findings from numerous researchers from across the world attest to this. A meta-analysis by Bohoussou et al. (2022) on the effects of CA on soil organic carbon (SOC) revealed that CA increased SOC by 21.39% and total nitrogen stock by 54.34%. Similarly, Das et al. (2022) reported that CA practices improved SOC stocks up to 19.10% in about 20 years, whilst in earlier studies, Thierfelder and Wall (2012) showed a 104% increase in SOM following the implementation of CA on sandy soils in Zimbabwe. Improving soil SOC levels is associated with increased soil structural stability, water infiltration and storage, nutrient retention and soil biodiversity. Improvements in structural stability result in reduced environmental degradation and enhanced soil quality. This is particularly important in SSA, where most agricultural soils are inherently fragile.

However, to reap these benefits, it is crucial to apply all three principles of CA simultaneously. The effective application of the three CA principles positively impacts soil physical properties, enabling the soil to capture and retain adequate rainfall, thus improving biomass production. Generating significant amounts of biomass is challenging for smallholder farmers who often need help to produce enough for surface retention and other farm purposes. Retention of residue is, therefore, a major deterrent for most smallholder farmers in SSA. These farmers typically rely on crop residues to feed their livestock. Consequently, some authors, e.g. (Wakindiki

et al. 2019), concluded that incorporating bio fertilisers could complement CA by increasing biomass production, enabling farmers to retain sufficient residues.

2.1 Local Research Initiatives in SSA

Information transfer, capacity development, and policy support are essential for the successful implementation of CA. The adoption of sustainable agricultural methods throughout the region is primarily promoted and supported by governments, non-governmental organisations, and international organisations. Through close collaboration, these organisations aim to address SSA's problems with food security, environmental sustainability, and rural development by utilising conservation agriculture's transformative potential. Several regional research initiatives advocate and implement CA principles in Sub-Saharan Africa (Table 1). These initiatives, among others, are actively researching, promoting, and implementing CA practices in Sub-Saharan Africa. They play a crucial role in improving agricultural productivity, enhancing soil health, and supporting the livelihoods of small-scale farmers in the region.

Table 1 Organisations advocating for the adoption and implementation of conservation agriculture in Sub-Saharan Africa

Research initiatives	Role
The African Conservation Tillage Network (ACT)	Established in 2002 to enhance agricultural productivity, sustainable land management and environmental conservation by promoting CA principles and practices in Africa.
The Africa Soil Health Consortium (ASHC)	Founded in 2013 to promote the adoption of integrated soil fertility management (ISFM) practices.
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)	Dedicated to enhancing agricultural productivity, resilience, and livelihoods in the semi-arid tropics is called the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). Its headquarters are in Hyderabad, India, and it was founded in 1972.
World Agroforestry Centre (ICRAF):	Multidisciplinary research organization whose goal is to advance the blending of trees with agriculture and landscapes. The Consultative Group for International Agricultural Research (CGIAR), which oversees its operations, created it in 1978.
Conservation Agriculture Zambia (CAZ)	Is a non-profit organisation devoted to promoting and implementing CA methods in Zambia. The main objectives of CAZ are to raise food security, increase agricultural output, and promote environmentally friendly farming methods throughout the nation.
International Maize and Wheat Improvement Center (CIMMYT)	Established in 1966 to secure global food security, eradicate poverty, and protect natural resources by sustainably increasing the productivity of maize and wheat systems. The organisation's research and development efforts are concentrated on enhancing crop varieties, advancing environmentally friendly agricultural methods, and enhancing the skills of farmers, scientists, and other stakeholders.

Table 2 Conservation Agriculture effects on soil quality, crop productivity

Objective and experimental treatments	Crop productivity	Soil	Reference
To investigate CA as a sustainable alternative for conventional maize production practices	–	CA increased total C content by 17.1 Mg ha ⁻¹ relative to CT	Dendooven et al. (2012)
To understand the trends of soil quality improvement in maize-based cropping systems in the first 5 years considered as a medium-term period	CA resulted in significant maize increases in the 5th year.	CA significantly increased soil organic matter and from the 4th year. Soil aggregates of >2 mm and Earthworm activity and increased under CA after 5 years.	Ligowe et al. (2017)
To determine the effects of CA on bulk density (BD), porosity, mean weight diameter (MWD) and penetration resistance (PR) in a semiarid province of South Africa (SA).	–	No-tillage increased soil organic carbon (SOC) compared to conservation tillage at the 0–5 cm depth. Tillage, crop rotation and residue management reduced MWD at the 0–5 cm depth	Nyambo et al. (2022)
Evaluated the impact of conventional practices and CA on SOC and profitability	No difference between CA and CT	SOC was high under reduced tillage than CT in clay soil but not in the sandy loam.	Swanepoel et al. (2018)
To evaluate the grain yield, mineral content, and nutrient yield of eight maize varieties grown in Malawi and assess how CA practices influence these parameters under field trial conditions.	Yield increases under CA treatments led to increased grain protein and Ee contents, no effect on the yields of K, Mg, Mn, P, Zn, and reduced Fe yield	–	Galani et al. (2022b)

Similar to its impact in other regions, CA has been demonstrated to have favourable effects on the soil quality in Sub-Saharan Africa (Table 2). Several factors, such as the initial soil conditions, the specific management practices employed, and how long they have been in operation, might affect how CA affects soil attributes. Leaving crop residues creates a protective layer that remains on the soil's surface, sheltering it from the sun's harsh rays and lowering evaporation (Shrestha et al. 2020). Moisture is retained longer, reducing the danger of drought and water stress, two common problems in Sub-Saharan Africa. As a result, residual moisture encourages microbial activity, stimulating nutrient cycling and organic matter breakdown, positively influencing the soil's chemical characteristics (Malobane et al. 2021).

Conservation agriculture has been essential in replenishing soil fertility in Sub-Saharan Africa, where many areas experience nutrient-poor soils. Farmers can promote nitrogen fixation, refilling the soil with this crucial nutrient for succeeding harvests using cover crops, legumes, and green manures (Nyambo et al. 2021).

Utilising organic matter, such as compost and animal manure, also increases the amount of nutrients in the soil and strengthens its structure, both of which improve the chemical qualities of the soil. The cumulative effect on soil chemical characteristics is significant as conservation agricultural practices continue to be adopted across Sub-Saharan Africa. Enhanced microbial activity, greater nutrient content, and improved soil structure all help to create more resilient and fruitful agricultural systems (Malobane et al. 2021). In the end, this improves not just farmers' access to food and their means of subsistence but also contributes to climate change mitigation through soil carbon absorption and decreased emissions of greenhouse gases.

According to Nyambo et al. (2022), CA techniques like minimal tillage or no-till aid in maintaining soil structure by retaining soil aggregates and reducing soil compaction. As a result, soil fertility increases and erosion decreases, allowing for better aeration, water infiltration, and root penetration (Malobane et al. 2020). As a natural mulch, crop residues left on the soil's surface lessen the effect of rain and improve water uptake (Steward et al. 2018). Because of the enhanced water retention caused by CA, the soil is more resistant to drought and waterlogging. Furthermore, crop leftovers used as mulch help increase the soil's organic matter content (Gura et al. 2022). By binding soil particles into stable aggregates and expanding the pores, organic matter contributes to better soil structure and facilitates easier water infiltration. Table 2 summarises research on the effect of CA on soil properties.

2.2 Techniques and Practices for Strengthening Crop Production

As already presented, CA is based on three principles i.e. diversified crop rotations, minimum tillage and permanent soil cover. As highlighted by Farooq and Siddique (2015), tillage was questioned in fragile systems around the 1930s by Edward H. Faulkner when dust bowls devastated vast areas of the Midwestern USA (Friedrich et al. 2012). In agriculture, most of the soil ecosystem functions are driven by the various macro and micro-organisms, which are found in the few top cm of the soil (Strauss et al. 2021). These organisms in this critical region of the soil feed mainly on the soil organic matter, and soil disturbance in this region has been observed to trigger rapid loss of soil organic matter resulting in soil degradation. Disturbing soil through tillage has the positive immediate effect of increasing aeration, which consequently exposes the protected organic carbon to oxidation by microbes that multiply under the increased aeration. The loss of soil organic matter through disturbances like tillage is the reason why land use changes have been indicated to contribute up to 21% of total carbon emissions (Strauss et al. 2021). This then brought the idea of protecting the soil through a process called conservation tillage to reduce soil erosion by wind or water whilst enhancing water use efficiency (Strauss et al. 2021).

With the introduction of the Green Revolution, the high utilisation of synthetic fertilisers promoted the *feed the crop* and not the *feed the soil to feed the crop*, strategy (Mupambwa et al. 2022). Apart from not promoting organic matter build-up in the farmer's fields, using fertilisers also promoted mono-culture systems, which consequently led to soil degradation and the build-up of pests and diseases. As indicated by Farooq and Siddique (2015), the continuous growth of a maize monocrop causes severe challenges such as perennial weeds, insect pests, leaf and soil diseases, and nematodes as the crop residues act as a safe haven for pests and diseases. As a solution to creating cultural methods of managing the pest and disease challenge under monoculture systems, diversified crop rotations have been observed to play a critical role as they create an opportunity to break pest and disease cycles (Strauss et al. 2021). For example, parasitic weeds like *Striga asiatica* depend on the availability of a host plant to germinate and develop, thus, introducing an alternative crop can be a crucial driver in reducing the spread of such weeds. In a study involving maize-velvet bean (*Mucuna pruriens*) rotation, weed densities were reported to decrease by up to 92% after 5 years (Mhlanga et al. 2015).

Besides being critical in driving cultural control of pests and diseases, crop rotations are also critical in driving biological nitrogen fixation in the soil. Legume crops can form symbiotic relationships with various microbes that allow them to fix atmospheric nitrogen into the soil. Though the ability to fix nitrogen varies across soils, legume species and environment, in a temperate environment in Australia, the nitrogen made available to a subsequent wheat was an average of 37 kg N per ha (Stagnari et al. 2017). In another study, Stagnari et al. (2017) also highlighted that nitrogen uptake by the subsequent crop after a legume was 23–59% higher across different soils. Due to these nutritional benefits, rotations with nitrogen-fixing legumes are recommended in CA systems.

With the advent of soil disturbance due to agricultural activities, the need to cover this disturbed soil can not be over-emphasized. The main reason for covering the soil is to protect the topsoil from disaggregation processes, mainly physical breakdown, caused by raindrops and strong winds. When the soil is uncovered the impact of raindrops can cause soil sealing, thus reducing water infiltration thus driving soil erosion (Calegari et al. 2020; Farooq and Siddique 2015). In CA systems, it is recommended to maintain soil cover as either permanent or semi-permanent, and a soil cover above 30% is recommended. The covering of soils can be achieved through the use of dead plant biomass or by using live crops called cover crops. Apart from protecting the soil from physical damage, adding organic soil cover complements the aspect of minimum soil disturbance by contributing to increased organic matter in the soil whilst also having the ability to act as part of the rotations. Furthermore, covering the soil with biomass has also been observed to suppress weed growth and increase natural enemies of pests and diseases (Calegari et al. 2020). As soil cover can be achieved using dead or live plants (cover crops), the choice of these cover crops depends on soil texture, biological activity, bulk density, biological activity, organic matter and nutrient status, and rainfall regime of the area. Various cover crops have thus been used, which can be either legumes or cereals such as pigeon pea (*Cajanus cajan*), velvet bean (*Mucuna* sp.), sunn hemp

(*Crotalaria juncea*), cowpea (*Vigna unguiculata*), lablab (*Dolichos lablab*), black oat (*Avena strigosa* Schreb), white oat (*Avena sativa*), radish (*Raphanus sativus*), vetches (*Vicia sativa* and *Vicia villosa*) among others.

All these three principles of CA expanded above have been designed to improve productivity on poor quality soils prevalent under resource poor smallholder farmers. The main benefits these three arms of CA have on cropping systems are summarised in Table 3.

2.3 Barriers and Challenges to Conservation Agriculture Uptake in Sub-Saharan Africa

On-farm studies have demonstrated that CA may not lead to any increase in soil properties or yield for one or several consecutive seasons (Nyambo et al. 2020b). As a result, smallholder farmers are frequently unwilling to continue using it (Giller et al. 2009). This is particularly true in Africa, where only 0.3% of the continent's total agricultural land is covered with CA, largely in the commercial farming sector (FAO 2011). According to Brinkman (2017), 90% of 1.2 million ha of CA in Africa are found in South Africa, Zimbabwe, Zambia, Mozambique, and Malawi. Several socioeconomic and biophysical parameters influence smallholder farmers' adoption of CA (Table 4). Some hindrances include the need for adapted implements for direct sowing and availability, residue management trade-offs, and cost and knowledge associated with using herbicides in CA (Nyambo et al. 2020a). Many smallholder farms show that many farmers are on a pathway towards CA and will undergo intermediary steps before full adoption. In the first step, farmers usually adopt no-till only, then after some time adopt either crop rotation or residue management before taking up all three CA principles. In the process to full CA adoption, it is unclear what changes occur in the short term with regard to soil physicochemical properties and yield.

2.4 Scaling up Conservation Agriculture Practices

A coordinated and multifaceted strategy involving numerous stakeholders, including governments, NGOs, international organisations, and local people, is needed to scale up CA in Sub-Saharan Africa. The strategies include prioritising CA by governments through policy support and incentives (Branca et al. 2022). This can be accomplished by giving tax incentives or other financial assistance for farmers switching to CA practices, as well as subsidies for CA-related goods, including seeds, machinery, and organic fertilisers. Such policies can also enhance access to resources by ensuring the inexpensive availability of seeds with CA adaptations, encouraging the use of organic materials with local availability for mulching and

Table 3 A summary of the various conservation agriculture principles and their effects on soil quality and crop growth

Conservation Agriculture principle	Experimental details	Duration of study and location	Major observations	Reference
Cover cropping with live crops and minimum tillage.	The treatments in this study consisted of three combinations established in a vineyard i.e. (i) minimum-tilled (MinTill) barley (<i>Hordeum depressum</i>) cover crop (CC) only minimally disked (2–3 cm depth) every second season and residues of the grapes and barley left on the surface, (ii) barley cover crop was under conventional tillage (Till) with disking (up to 10 cm) with residue incorporation, (iii) conventional tillage with disking and no cover crop (NoCC) (up to 10 cm).	The treatments were established from 2003–2010 but the measurements were only done over 2 years i.e., 2009 and 2010. The study was done at the University of California, Davis, Napa Valley, California.	The average carbon in soil was highest in the minimum till with cover crop treatment with an average C of 2.46%. Overly, the average C in the soil followed the order MinTill+CC > Till+NoCC > Till + CC with 2.46%; 2.14% and 2.10% average C, respectively. Similarly, the soil C was 23.6, 20.2 and 20.5 Mg/ha ² , for the MinTill+CC, Till + CC, Till+NoCC, respectively. However, across the 2 seasons where measurements were made, there was no consistent trend on the annual emissions of CO ₂ and N ₂ O.	Wolff et al. (2018)
Reduced tillage	The soil was tilled either conventionally (CT) by mouldboard ploughing or according to reduced non-inversion tillage (RT) with a chisel plough, with a soil depth of about 30 cm for all treatments. To these treatments, manure was applied at 0, 15 and 45 Mg/ha.	The treatments were established over 3 seasons from 2008 to 2012	There was no significant difference between the CT and RT treatments on total organic carbon (TOC) in the soil, though the 0–10 cm soil layer tended to have higher TOC under reduced tillage relative to the conventional tillage. However, the microbial community structure represented by microbial biomass, fungi, bacteria, actinomycetes was significantly higher for RT compared to CT.	Willekens et al. (2014)

(continued)

Table 3 (continued)

Conservation Agriculture principle	Experimental details	Duration of study and location	Major observations	Reference
Tillage and residue retention.	The experiment was commenced with two treatments based on soil disturbance levels i.e., strip tillage (ST) and conventional tillage (CT), and two residue retention levels, low (LR) and high (HR). In the CT treatment, soils were ploughed each season at depths of 15 cm incorporating the crop residues. For the ST treatments were kept undisturbed except for a 3 cm furrow for planting.	The experiment was established in 2012 until 2018 at the Bangladesh Agricultural University Experimental Farm.	After seven consecutive years of CA practices, microbial biomass carbon increased by 34%, while specific maintenance respiration (qCO_2) decreased by 23% in ST as compared with CT. The total organic carbon, particulate organic carbon, and permanganate oxidizable C, were increased by 15%, 22.4%, and 22%, respectively, in ST compared with CT and by 21.1%, 20.9%, and 40.9%, respectively, in HR compared. Wwith LR.	Begum et al. (2022)
Crop rotation with or without tillage.	The field experiment had 3 types of crop rotations (i) CR1 spring wheat monoculture, (ii) CR2 2-year rotation (spring wheat—spring turnip rape (<i>Brassica rapa</i> subsp. <i>oleifera</i>)—spring wheat—spring barley) and (iii) CR4 4-year rotation [spring wheat—spring turnip rape—spring barley—field pea (<i>Pisum sativum</i>)]. These rotations were practiced under tillage and no tillage systems.	The field experiment was established at the research station of Luke Natural Resources Institute Finland, in Jokioinen in southwest Finland between 2005–2017.	In the most diverse crop rotation (CR4), the average spring wheat yield was on average 21% higher than the yield in the wheat monoculture CR1. In CR2, where wheat was cultivated every second year, the average yield. was 15% higher than in the wheat monoculture. The average nitrogen uptake in ploughed plots in CR4 was 14% higher and the average phosphorous uptake 17% higher than in the CR1 treatment.	Jalli et al. (2021)

soil cover, and facilitating access to suitable equipment for reduced tillage. Through private-public partnerships, governments can increase awareness of CA through enhanced training and extension services. The dissemination of information and technical support to farmers regarding CA principles and how to apply them to local conditions can be greatly aided by extension workers. Extension workers are the the

Table 4 Description of barriers to adoption of conservation agriculture in sub Saharan Africa

Barrier/ challenge	Description	Reference
Limited Awareness and Knowledge	a lack of understanding of the advantages and appropriate application of CA techniques. Increasing awareness and arming farmers with the appropriate information requires the use of extension services and training programmes.	Lee and Gambiza (2022)
Access to Resources:	Accessing resources like better seeds, cover crops, organic matter for mulching, and conservation tillage equipment is frequently difficult for smallholder farmers. Adoption is hampered by the resources' high prices and scarce availability.	Brown et al. (2018)
Risk aversion	There is some risk involved in switching from conventional agricultural practices to CA because farmers may be unsure of the results and possible changes in production. Farmers may be hesitant to implement CA methods out of concern for crop loss or decreased income during the transition period.	Giller et al. (2009)
Land tenure and ownership	Insecure land tenure and unclear land ownership can deter farmers from making long-term investments in sustainable practices like CA. Without ownership rights, farmers may be less motivated to invest in soil conservation measures or make improvements to the land.	Lovo (2016)
Labor intensiveness	Certain CA techniques, like mulching, weeding and cover crops, can be labor-intensive, especially for smallholder farmers who frequently have few labor resources. This can be very difficult, especially when agriculture is at its busiest.	Giller et al. (2009)
Socio-cultural factors	Farmers may find it challenging to adopt CA since traditional values and cultural customs may support conventional agriculture operations. Agrarian practices may be resistant to change because of social conventions and perceptions about how farming should be done.	Ntshangase et al. (2018)
Access to credit and finance	Smallholder farmers in sub-Saharan Africa frequently face difficulties due to their limited access to credit and finance. Many farmers who lack the appropriate financial resources may find it difficult to implement CA methods due to the initial expenditure required.	Langyintuo (2020)
Pests and diseases	The prevalence of diseases and pests in some areas may make it difficult for farmers to implement CA systems, especially if they are unaware of integrated pest control strategies that are appropriate for CA systems.	Paudel et al. (2020)

vehicle for CA knowledge sharing between farmers- farmers and research-farmers. Early adopters who are successful can share their knowledge and best practices with nearby farms, igniting interest in CA adoption and a sense of community ownership.

3 Conclusion

In conclusion, expanding CA techniques in Sub-Saharan Africa has enormous potential for tackling issues related to food security, climate change, and the environment. The region can create more robust and wealthy agricultural systems while protecting its natural resources for future generations by encouraging sustainable agriculture practices and empowering smallholder farmers. Governments, NGOs, and international organizations must work together to develop a comprehensive strategy to overcome obstacles to its CA adoption in the region. Along with governmental changes and market interventions, providing farmers with technical assistance, training, and financial support can help establish a climate conducive to the adoption of CA and promote sustainable agricultural development in the area.

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Increasing Productivity Through Enhanced Water Use Efficiency in Marginal Soils



M. E. Malobane and P. Nyambo

1 Introduction

Africa generally experiences water scarcity due to frequent droughts – a phenomenon associated with extreme high temperatures as a result of climate change (Mpandeli et al. 2018; Nhamo et al. 2019; Dube et al. 2020; Leal Filho et al. 2022). Temperatures in Africa are projected to rise, while precipitation in many regions of the continent is expected to decrease (Almazroui et al. 2020; Ayugi et al. 2021). In addition, drought frequencies are projected to increase in certain African regions (Almazroui et al. 2021; Ayugi et al. 2022). The available water is already in high demand from different users, including industry, irrigated agriculture, and households (Abou Zaki et al. 2018; Tian et al. 2018; Ungureanu et al. 2020; Khilchevskiy and Karamushka 2021). Water scarcity is therefore likely to remain a problem in Africa for years to come.

Agriculture is very important for the African economy, the development of the continent, and as a source of income for many families (Armah et al. 2010; Diaio et al. 2010; Collier and Dercon 2014). Approximately 70% of the African population makes a living through agriculture, which contributes to a third of the continent's national income (Armah et al. 2010; Biteye 2016). Most agricultural enterprises in Africa depend on being rainfed, making the continent more vulnerable to climate change and variability (Armah et al. 2010; Shiferaw et al. 2014; Derbile et al. 2016). For those reasons, enhancing water use efficiency (WUE) in

M. E. Malobane (✉)

University of South Africa, Department of Agriculture and Animal Health,
Florida, South Africa
e-mail: malobme@unisa.ac.za

P. Nyambo

University of Fort Hare, Department of Agronomy, Alice, South Africa

Africa is vital for sustainable food production (Kadigi et al. 2019; Uhlenbrook et al. 2022).

WUE is defined as crop yield in a given area (kg/ha) per given quantity of water (mm) (Hatfield and Dold 2019). The main aim of enhancing WUE is to increase food security and income, with low water input (Xue et al. 2017). In arid and semi-arid regions, an increase in WUE has the potential to augment incomes, boost employment, and enhance nutrition for families (Hatfield and Dold 2019), which makes it imperative in the fight to curb growing water scarcity and food insecurity. Agronomic practices that help to achieve WUE include water harvesting, the use of irrigation, and increased soil water conservation (Attwater and Derry 2017). The goals of these agronomic practices are to enhance transpiration, and decrease evaporation and water runoff.

Work on WUE in the agricultural sector dates from the 1960s, and since then significant research has been done to contribute to this field (Hatfield and Dold 2019). Gaining knowledge from different studies can thus aid in providing recommendations to farmers – especially those in Africa who have to deal with marginal soils. The aim of this chapter is to gather literature on WUE practices under marginal soils, and to offer recommendations which are suited to African conditions.

2 Water Scarcity in Africa

Water scarcity due to climate change is widespread across Africa, and threatens many livelihoods (Leal Filho et al. 2022). According to Musse (2021), several regions experience either water scarcity or water stress. Approximately 51% of people in sub-Saharan African countries are without safe drinking water, and the number is projected to keep growing (Besada and Werner 2015). Many inhabitants of rural communities rely on surface water sources which tend to run dry, compelling them to drink unsafe water (Muller et al. 2009). Compared to most developed countries where one person uses 200 L of water per day (Vilakazi et al. 2019), people in Africa use approximately 5 L per person per day, which is far less than the recommended minimum of 20 L a day, per person (United Nations Children's Fund [Unicef] 2017), for social, health-related and economic development.

Several regions in Africa are classified as arid or semi-arid (Kasei 2012). Due to climate change, these regions are projected to keep expanding and encroaching on fertile soils (Spinoni et al. 2021). Soils in arid and semi-arid regions are regarded as the most fragile, due to the harsh environmental conditions associated with climate change (Abdelhak 2022). According to Ayangbenro and Babalola (2021), soils in arid and semi-arid regions are characterised by soil degradation, low fertility status and water scarcity, all of which have a negative impact on crop production and yield. Degraded soils with low fertility status under limited water resources are classified as marginal soils (Shahid and Al-Shankiti 2013). In addition, arid and semi-arid soils have low water-holding capacity and contain little organic matter (Alori et al. 2020; Ayangbenro and Babalola 2021). High temperatures with low

precipitation and high temporal and spatial variability are amongst the other problems affecting arid and semi-arid regions (Alori et al. 2020). According to Ofori et al. (2021), temperatures in Africa are projected to increase by 3–6 °C above the global average. The rise in temperatures, low and erratic rainfall, soil degradation and soils' low water-holding capacity pose significant threats to sustainable food security in Africa. Finding ways of enhancing WUE on the continent is thus of paramount importance for food security and nations' sovereignty.

3 Irrigation Scheduling as a Way of Enhancing Water Use Efficiency in Marginal Soils

Low rainfall in arid and semi-arid regions is a key cause of low crop yields and food insecurity (Mancosu et al. 2015; van Rooyen et al. 2017). The application of irrigation has been promoted as one way of enhancing food security (Oteng-Darko et al. 2018; Unver et al. 2018; Yang and Gao 2021), but water scarcity and competition for water resources by other users remain a challenge to agriculturalists (Mancosu et al. 2015; Chakkaravarthy and Balakrishnan 2019; Eshete et al. 2020; Tzanakakis et al. 2020). For this reason, it is imperative to find ways of enhancing WUE and managing the water challenges facing the irrigated agriculture sector (Kelly et al. 2021). One way of increasing WUE in agriculture, is through irrigation scheduling (Kelly et al. 2021).

Irrigation scheduling involves irrigating only the quantity of water which a crop requires, while avoiding water stress and maximising crop yields (Adeyemi et al. 2017). Such scheduling seeks to increase water use efficiency or productivity (Koech and Langat 2018). Several authors have reported that water management can enhance WUE in Africa under arid and semi-arid conditions: for example, Materu et al. (2018), who conducted a study in Tanzania, reported that the application of water at an 80% system of rice intensification (SRI) increased the crop yield by 1.57 tons/ha, and saved 33% (345 mm) of water, when compared to a conventional flooded (CF) system. The authors further reported that 80% SRI had the highest water economic productivity of \$20.27/ha, while CF delivered \$12.89/ha (Materu et al. 2018). Covering up to 80% of SRI from CF, water can support 50% of irrigated rice in Tanzania (Materu et al. 2018). Mboyerwa et al. (2021) also found that drying and wetting irrigation management increased water productivity by 8.3%, compared to CF under rice production in Tanzania. Gadédjisso-Tossou et al. (2018), conducting a study in northern Togo, found that controlled deficit irrigation gave the same yield as full irrigation treatment in maize production. Thus, controlled deficit irrigation was recommended as an ideal management system in northern Togo, for maize production which saved water (Gadédjisso-Tossou et al. 2018). The findings of that study were later supported by Gadédjisso-Tossou et al. (2020), who found that 80% of full irrigation gave the same maize yield as full irrigation in northern Togo. A study by Attia et al. (2021) found that an irrigation deficit of up to

50% of available soil water could be applied in sandy soils in North Africa, without significantly reducing maize yields. Asmamaw et al. (2021) reported that deficit irrigation can improve the WUE of maize, onion, tomato, and wheat, more so than a fully irrigated system.

4 Agricultural Practices to Enhance Soil Water Conservation

African lands are largely susceptible to soil degradation, and have low water-holding capacity—factors which threaten food security and the livelihoods of many on the continent (Diop et al. 2022). Soil degradation can also be defined as the reduction of soil production and its ability to carry out ecosystem services and functions, as a result of a decline in its chemical, physical, and biological properties (Nunes et al. 2020). Approximately 65% of degraded agricultural land is in Africa (Thiombiano and Tourino-Soto 2007). In some parts, soil degradation is severe (Nkonya et al. 2016). Conventional tillage, lack of inputs, monoculture, and low organic matter due to the removal of crop residues are all associated with an increase in soil degradation (Saturday 2018; Srinivasarao et al. 2021; Cárceles Rodríguez et al. 2022). Soil degradation threatens food security by reducing crop yields (Pozza and Field 2020); it also leads to a decline in food nutrition, and increases poverty (Barbier and Hochard 2018; Nunes et al. 2020). According to Eswaran et al. (2019), land degradation also leads to financial losses, therefore adopting agricultural practices that enhance or improve soil and water conservation is crucial for food security and a thriving economy (Darkwah et al. 2019; Diop et al. 2022). Soil and water are, after all, the most important resources in agriculture (Nyamekye et al. 2018).

Soil and water conservation aims at minimising soil loss due to erosion while enhancing soil quality and fertility, infiltration and water-holding capacity (Wolka et al. 2018; Kumawat et al. 2020; Diop et al. 2022), placing such conservation efforts at the centre of sustainable agriculture (Abiye 2022). In this section, only studies conducted in Africa, on conservation agriculture (CA) and *in situ* rainwater harvesting, are discussed since both can enhance soil water content at the rootzone (Biazin et al. 2012; Manyanga et al. 2022). In addition, both are regarded as promising practices for enhancing food security in Africa, under climate change regimes (Vohland and Barry 2009).

4.1 *The Effect of Conservation Agriculture on Soil and Water Conservation in Africa*

For decades, CA has been promoted by different organisations, leading to valuable research being conducted on this continent (Mango et al. 2017; Kassam et al. 2022). CA is promoted as a win-win technology, as it can enhance and conserve soil and

water, while also conserving the environment (Mango et al. 2017; Malobane et al. 2018; Kaweesa et al. 2021). The application of CA is based on three principles: minimum soil disturbance, crop rotation, and the retention of crop residues as soil cover (Food and Agriculture Organization [FAO] 2015).

The application of CA enhances soil quality and fertility as well as moisture retention, leading to increased crop yields under semi-arid conditions (Abdullah 2014; Abdallah et al. 2021; Mbanye et al. 2021; Cárcel Rodríguez et al. 2022). Malobane et al. (2021) found that the application of CA enhanced soil aggregate stability, aggregate bending agents and aggregate microstructure in marginal soils in South Africa under semi-arid conditions. The aforementioned study aligns with that of Nebo et al. (2020) and Nyambo et al. (2022), who found that the application of CA enhanced aggregate stability, porosity, hydraulic conductivity and penetration resistance in such soils. The positive effects of CA on soil's physical properties were also reported by Mason et al. (2015) and Partey et al. (2018), who studied marginal soils in West Africa, under semi-arid conditions. Similar studies include those of Eze et al. (2020) in Malawi, Thierfelder et al. (2015) in southern Africa, Entz et al. (2022) in East Africa, Corbeels et al. (2015) in sub-Saharan Africa, and Marongwe et al. (2011) in Zimbabwe.

An increase in soil organic carbon (Swanepoel et al. 2018; Gonzalez-Sanchez et al. 2019; Mtyobile et al. 2019a; Wakindiki et al. 2019; Entz et al. 2022), soil nutrient availability (Naab et al. 2017; Mtyobile et al. 2019b; Malobane et al. 2020a; Devkota et al. 2022), soil biology (Malobane et al. 2020b; Mcinga et al. 2020; Muzangwa et al. 2020; Nyambo et al. 2021), infiltration and water content (Sithole et al. 2019; Eze et al. 2020; Mutuku et al. 2020; Mbanye et al. 2021; Mhlanga and Thierfelder 2021) were all reported after the application of CA to African soils under semi-arid conditions.

The increase in crop yields after the application of CA, compared to CT in African marginal soils under semi-arid conditions, is well recorded. For example, Assefa et al. (2019) found that, under those conditions, CA increased the yield of tomato, garlic, cabbage, onion, and sweet potato in sub-Saharan regions, when compared to CT. Descheemaeker (2020) reported that CA increased maize yields in sub-Saharan semi-arid regions, when compared to CT. The application of CA was also found to increase maize yield, when compared to CT, under semi-arid conditions in East and southern Africa (Rockström et al. 2009; Nyagumbo et al. 2020). Ngetich et al. (2014) reported that maize grain yield was seven times higher under CA than under CT, in semi-arid conditions in Kenya. The authors also noted that CA decreased maize yields when rainfall was sufficient (Ngetich et al. 2014). Notably, Mbanye et al. (2021) found that CA increased maize yield, when compared to CT, under high rainfall conditions in sandy soils. Sithole and Magwaza (2019) found that CA increased maize yield under semi-arid conditions in South Africa, but only under high nitrogen fertilizer application. Thierfelder et al. (2013) reported that maize yields in CA systems were 24–40% greater than with CT in Malawi's semi-arid regions, and that maize yields under CA were affected by rainfall infiltration. Thus, the benefits of CA for crop yields are a function of climate, soil type/conditions and agronomic practices (Swanepoel et al. 2018).

In African countries under different crops, water productivity was found to be higher under CA, than under CT (Thierfelder et al. 2013; Assefa et al. 2019; Mbanyele et al. 2021), which might explain why CA rendered high crop yields under limited water conditions. This makes CA an ideal practice for Africa's semi-arid regions, as projections show that rainfall will decrease due to climate change.

4.2 The Effects of In Situ Rainwater Harvesting on Water Conservation and Productivity in Africa

Rainwater harvesting (RH) is a promising practice that can enhance food security in areas experiencing water scarcity (Velasco-Muñoz et al. 2019; Piemontese et al. 2020). For this reason, RH has received significant attention from researchers as a way of enhancing agricultural intensification in arid and semi-arid regions (Velasco-Muñoz et al. 2019). The application of *in situ* RH is common amongst smallholder farmers, where technologies that influence rainfall use efficiency in agricultural fields are implemented (Andersson et al. 2011). The main purpose of RH practices is to trap or retain rainwater where it is needed during rainfall, thus increasing the quantity of water stored in the soil profile (Mahmoud and Alazba 2015). *In situ* RH practices include conservation tillage, contour farming, small/infiltration pits, semi-circular and trapezoidal bunds, small runoff basins and mulching, potholing, and tied-ridging (Monde et al. 2012; Mudatenguha et al. 2014).

The benefits of *in situ* RH for crop yields in Africa are well summarised by, amongst others, Biazin et al. (2012), Dile et al. (2013), Lebel et al. (2015) and Piemontese et al. (2020). The authors reported that the application of *in situ* RH practices can increase crop yields by up to 100%, compared to control without RH. This is because *in situ* RH practices were found to increase soil moisture in the rootzone in arid and semi-arid regions in Africa, when compared to the control (Biazin et al. 2012; Yosef and Asmamaw 2015; Grum et al. 2017a). In addition, *in situ* RH practices were reported to reduce soil loss by up to 94% (Grum et al. 2017a, b; Sultan et al. 2018; Ebabu et al. 2019) and nutrient loss by up to 68% for phosphorus and 63% for nitrogen, when compared to the control depending on the site (Grum et al. 2017b). Thus, the application of *in situ* RH practices can enhance food security and economic returns across many regions of Africa (Biazin et al. 2012).

5 Conclusion

Conservation agriculture is one of the most important agronomic practices for enhancing soil and water conservation, WUE and crop yield under arid and semi-arid conditions in Africa. RH practices also enhance soil water content, infiltration,

soil fertility and crop yields in the aforementioned marginal soils. Site conditions are, however, important when selecting which practices to use under CA and RH.

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Promoting Low-Input Agricultural Practices to Improve Marginal Lands for Sustainable Crop Production and Food Security in Sub-Saharan African Countries



Salmina N. Mokgehle, Nadia A. Araya, Funso R. Kutu, Manaka J. Makgato, Motiki M. Mofokeng, Beverly M. Mampholo, Batizi Serote, and Hints T. Araya

1 Introduction

The world's population doubled in the last century, making it critical to use sustainable farming methods to ensure productivity and food security (Wik et al. 2008). Over 20% of the world's food supply is produced by low-input smallholder farmers, who make up half of all food producers (Fess et al. 2011). Smallholder farmers with limited resources have demonstrated a more significant trend toward minimal input farming methods nowadays, focusing on sustainability-related factors (Myeni et al. 2019). Low-input farming techniques, which rely primarily on internal inputs, are a potential solution to many of the issues caused by high-input farming techniques, which have been used for decades and have been implicated in numerous environmental issues like water pollution and biodiversity loss. While most smallholder farmers in various sub-Saharan African regions have primarily relied on high-input farming techniques, the high load of external farm inputs has increased nutrient leakage and reduced soil fertility, pesticide contamination, deterioration, and erosion (Stewart et al. 2020). Although the availability of exogenous chemical fertilizers for crops has expanded in many areas, their use in Africa is restricted because of their high cost, inaccessibility to smallholder farmers with low resources, and possible environmental degradation (Muluneh et al. 2022).

S. N. Mokgehle (✉) · F. R. Kutu

School of Agricultural Sciences, University of Mpumalanga, Mbombela, South Africa

e-mail: Salmina.Mokgehle@ump.ac.za

N. A. Araya · M. M. Mofokeng · B. M. Mampholo · B. Serote · H. T. Araya

Agricultural Research Council - Vegetables, Industrial and Medicinal Plants, Roodeplaat (ARC - VIMP), Pretoria, South Africa

M. J. Makgato

Agricultural Research Council-Stellenbosch, Infruitec-Nietvoorbij, Stellenbosch, South Africa

Environmental degradation, such as poor soil quality, nutrient depletion, and climate change affecting smallholder farmers, is linked to the slow increase in agricultural output. It is against this background that previous research has demonstrated that low-input systems rely on improved on-farm resource management, which leads to a more sustainable agroecosystem because there is less reliance on off-farm resources (Giller et al. 2021).

The adoption of sustainable agriculture as a practical approach refers to practices considering low-input farming methods that are ethically responsible, financially feasible, and socially equitable (Piñeiro et al. 2020). The long-term development of farming systems that are productive and lucrative, conserve the natural resource base, protect the environment, and improve health and safety is the goal of sustainable agriculture through low input.

Low-input marginal agricultural land refers to restrictions that, when taken together, are too great for sustained application of a given use, are susceptible to land degradation due to inappropriate human intervention, have already lost some or all of their productive capacity as a result of inappropriate human intervention, and also include contaminated and potentially contaminated sites that pose a risk to people, water, and ecosystems (Von Cossel et al. 2019). Smallholder farmers frequently employ mixed systems in marginal areas, which combine agriculture with other economic pursuits to distribute the risk. Low-input methods and skilled management must be tapped into to promote cooperative activities in ecologically and economically sound contexts. The method and strategies emphasize cultural and management methods such as crop rotation, animal manures, and conservation tillage to prevent soil erosion and nutrient losses and preserve or improve soil productivity. To maintain the long-term sustainability of existing production levels, crop patterns must be better matched to the productive potential and environmental restrictions of climate and topography. While there are advantages to low-input systems and sustainable production, there are also advantages to making better use of local knowledge and practices, as well as innovations in farming methods that are widely used but are not yet fully understood by researchers and adopted by farmers. The cited articles in these reviews indicated that low-input agricultural practices could improve productivity through sustainable approaches (Zwane, 2020; Mokgehle et al. 2021; Myeni et al. 2019).

The low-input agricultural strategy, which suggests and supports significant changes to traditional agriculture to make it more environmentally, socially, economically, and environmentally friendly, incorporates the sustainability concept (Singh and Singh 2017). Intercropping, crop rotation, biostimulant treatments, conservation farming, minimal tillage, and integrated pest control techniques are some examples of sustainable low-input agriculture ideas that can be used to solve environmental issues. The emphasis is still quite technological, emphasizing the necessity to reduce limiting factors to boost productivity, even if hundreds of more sustainable research initiatives and technological development attempts have occurred.

This chapter focuses on adopting and promoting low-input agricultural practices to improve marginal lands for sustainable crop production and food security. The section below delineates some of the principles associated with low-input agriculture with a view to promote and improve marginal lands.

2 Conservation Agriculture Principles for Marginal Lands

The phrase “Conservation Agriculture” was first used in the late 1990s before the World Congress on CA in Madrid in 2001 (Giller et al. 2015). Nowadays, there is still a wide variety of methodologies and practices ideal for improving crop productivity of marginal lands. Conservation agriculture (CA) combines methods and techniques that guarantee greater agricultural productivity and profitability while enhancing the environment and soil health (Cárceles Rodríguez et al. 2022). Conservation agriculture attempts to provide high agricultural yields while lowering production costs, preserving the fertility of the land, and preserving water, which are common characteristics of non-productive marginal lands. Globally, the type of conservation agricultural systems depend on farm size, and the input usage intensity. Research has shown that these systems improve the productivity of marginal lands. Conservation agriculture minimises soil disturbance, strategic timing of planting and utilizing crop residue to retain moisture and enrich the soil (Cárceles Rodríguez et al. 2022). Over the past 50 years, erosion in Southern Africa has increased while soil fertility has deteriorated (Vanlauwe et al. 2017). In addition to reducing the nutrients in the soil and allowing rain and wind to wash the nutrients away, heavy ploughing and continuously growing the same crop on the same plot (mono-cropping) also cause erosion and contribute to marginalization of areas (Chuma and Hagmann 1995).

The foundation of practising conservation farming in marginal lands is based on several ideas all aimed at creating sustainable agriculture. This can be achieved through resource-conserving and low-external input agriculture to diversify the understanding of various CA practices (Landers et al. 2021). The implementation of CA has enhanced factor productivities, grain and biomass yields, and soil quality, according to research results from marginal areas with mediterranean settings in several nations (Bashour et al. 2016; Mrabet et al. 2012). The widespread use and applicability of CA to dryland areas are advantageous to those regions throughout the drier months of the year through greater groundwater replenishment rates, considerable reductions in runoff losses, and improved water infiltration (Mrabet et al. 2012). The adoption of conservation agriculture for marginal lands is guided by the three most crucial principles of little to no soil disturbance, permanent soil cover, and crop rotation (Landers et al. 2021). Table 1 summarizes the impact of the different benefits of conservation agriculture principles on providing different ecosystem services, including marginal lands. The principle of permanent soil cover and crop rotation exhibited the highest impact regarding the potential benefits of conservation agriculture.

Table 1 Conservation agriculture principles and solutions to marginal lands

Potential benefit	Principle 1 (Less tillage)	Principle 2 (Permanent soil cover)	Principle 3 (Crop rotation)
Increase in soil matter	Moderate impact	High impact	Moderate impact
Reduction of soil evaporation	Moderate impact	High impact	Moderate impact
Biodiversity enhancement	Moderate impact	Moderate impact	High impact
Retain residues	Moderate impact	High impact	High impact
Rotation of different species	Moderate impact	Moderate impact	High impact
Reduced soil compaction	High impact	Moderate impact	Moderate impact

Landers et al. (2001, 2021)

3 Restoring Organic Matter Content of Marginal Lands

The restoration of the organic matter content of marginal lands is a process that involves adding organic matter to the soil to rebuild soil fertility and productivity. Organic matter acts as a nutrient reservoir, improves soil structure, and aids water infiltration and retention in marginal lands (Lal 2015). Because of low soil fertility, erosion, or other factors, marginal lands are unsuitable for profitable agricultural production (Haynes 2000). Restoring organic matter content in these lands is an important step toward increasing productivity and sustainability. Organic matter is essential for soil health because it increases water retention, nutrient availability, and soil structure (Hussain et al. 2021). However, due to unsustainable land use practices, the organic matter content of many marginal lands has been depleted over time. Restoring organic matter content in marginal lands is a difficult task that must address several issues. One of the most significant challenges is a lack of organic inputs, such as manure and compost, which are critical for increasing organic matter in the soil. Another issue is the presence of contaminants in the soil, such as heavy metals and pesticides, which can inhibit the growth of microorganisms that decompose organic matter (Alengebawy et al. 2021).

Furthermore, the degraded soil structure in marginal lands makes organic matter incorporation and retention difficult. Several strategies can be employed to restore organic matter content in marginal lands. One approach is planting cover crops are between cash crops to protect the soil from erosion and add organic matter to the soil as it decomposes (Kocira et al. 2020). Another approach is to use conservation tillage practices such as no-till or reduced tillage, which reduce soil disturbance and allow organic matter to accumulate in the topsoil. Incorporating organic amendments, such as compost and manure, can also provide nutrients and organic matter to the soil. Restoring organic matter content in marginal lands can have several advantages. It can improve soil health and fertility, resulting in higher crop yields and improved food security. Second, it can help prevent water pollution and protect downstream ecosystems by reducing soil erosion and runoff. Finally, it can sequester carbon in the soil, reducing greenhouse gas emissions and thus mitigating climate change. Several success stories show the value of restoring organic matter content in marginal lands. Farmers in India have improved soil health and crop

yields by combining cover cropping, conservation tillage, and organic amendments (Duddigan et al. 2023). The Conservation Reserve Program in the United States has restored over 20 million acres of marginal lands by planting native grasses and other vegetation, which has improved soil health and provided wildlife habitat (Stubbs 2014). Restoring organic matter content in marginal lands is critical to better soil health, increased crop yields, and climate change mitigation. While there are several obstacles to overcome, several effective strategies can also be used for a more sustainable future for agriculture and the environment by restoring organic matter content in marginal lands.

4 Improve Crop Diversity

Poor soil quality, low rainfall, and high susceptibility to erosion are common characteristics of marginal lands. Typically, these lands are unsuitable for traditional agricultural practices, making it difficult for farmers to produce crops that can sustain their livelihoods. Improving crop diversity on marginal lands is critical for food security, poverty reduction, and climate change mitigation. Marginal lands are frequently found in areas characterized by harsh environmental conditions such as drought, extreme temperatures, and poor soil quality (Gomiero 2016). These conditions make it difficult for farmers to cultivate crops that thrive in such conditions.

Furthermore, marginal lands are frequently overlooked by governments and private investors due to their low economic potential, exacerbating the difficulties faced by farmers in these areas. Crop diversity refers to the variety of crops that can be grown in a specific location. Farmers can reduce their reliance on a single crop and increase their resilience to environmental shocks such as drought or disease outbreaks by increasing crop diversity on marginal lands. Crop diversity also has environmental benefits, such as improved soil health, reduced erosion, and increased biodiversity (Michler and Josephson 2017). Several strategies can be used to increase crop diversity on marginal lands. One strategy is introducing new crop varieties that are more adapted to the local environment and produce higher yields.

Another strategy is to encourage agroforestry, which is planting trees alongside crops to provide shade, prevent erosion, and improve soil fertility. Intercropping, crop rotation, and cover cropping can also increase crop diversity and soil health. There have been numerous successful examples of increasing crop diversity on marginal lands. In Ethiopia, for example, the Tigray region has implemented a regreening program that involves planting trees and shrubs on degraded lands to restore soil fertility and promote biodiversity (Eshetie et al. 2021).

Similarly, the state of Andhra Pradesh in India has implemented a program called 'Zero Budget Natural Farming', which promotes natural farming techniques like intercropping, mulching, and composting to improve soil health and crop diversity (Khan et al. 2019). Improving crop diversity on marginal lands is critical for achieving sustainable agriculture, reducing poverty, and mitigating the effects of climate change. While numerous obstacles can be overcome, numerous successful

examples and strategies can be used to achieve this goal. Governments, private investors, and farmers can work together to create a more resilient and sustainable future.

5 Cover Cropping

Cover crops are generally defined as any non-cash crop grown in addition to the main cash crop. These crops can potentially reduce soil erosion, conserve moisture, improve soil structure, encourage water infiltration, limit pest and disease outbreaks, and provide supplemental minerals to the following crops on marginal lands (Strauss 2019). Although cover cropping has several advantages, trade-offs and restrictions must be considered, as with any management strategy (Fritz 2017; Brodt 2017). Cover crops may have a variety of direct and indirect effects on the nutritional status of the soil, which is defined as the physical, chemical, and biological characteristics closely associated with nutrient availability. The best cover crop for a given area is determined by several factors, including climate, soil type, and intended use. Figure 1 stipulates the indirect effects of cover crops and their contribution to soil nutrient statuses, such as an increase in microbial biomass, an increase in organic matter, and an improvement of the soil structure. The indirect benefits stipulated in Fig. 1 date back to Roman Empire and are widely used as farmer's practices (FAO 2017).

A wide range of crops, including cereals, legumes, root crops, and oil crops, can be utilized as vegetative covers, and each has unique advantages for the health of the soil (Quintarelli et al. 2022). Particularly, some species of cover crops may increase the amount of nitrogen (N) in the soil by fixing atmospheric nitrogen or acting as a catch crop to capture nutrients lost during the preceding crop's nutrient leaching due to their fibrous root systems (Scavo et al. 2022). Figure 2 stipulates the direct effects of the path of cover crops on the soil nutrient status, ranging from the release of organic nutrients, uptake of nutrients by plants, and the ability of the plants to fix nitrogen (e.g., leguminous crops).

Farmers must carefully plan and manage crop rotations to successfully implement cover cropping. This includes choosing suitable species, timing the planting and harvesting, and ensuring adequate seed-to-soil contact. Farmers should also consider using cover crops with other conservation practices like reduced tillage and integrated pest management. Farmers can improve soil health by implementing these practices, lowering costs, and increasing profitability. Despite the numerous advantages of cover cropping, its implementation is fraught with difficulties and limitations. Cover crops, for example, necessitate more time and resources to manage, which may be difficult for some farmers to accommodate.

Furthermore, cover crops may not be appropriate for all soils or climates, and their effectiveness may vary depending on local conditions. Cover cropping can be a valuable tool for improving soil health and productivity on marginal lands with careful planning and management. Cover cropping is a good way to improve soil

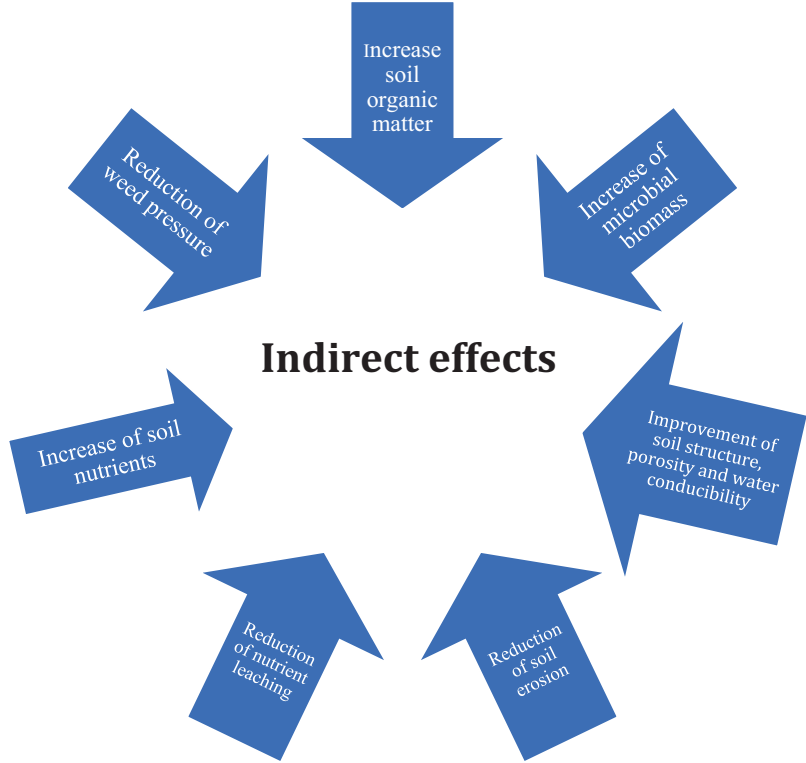


Fig. 1 Indirect effects of cover crops on the soil nutritional status

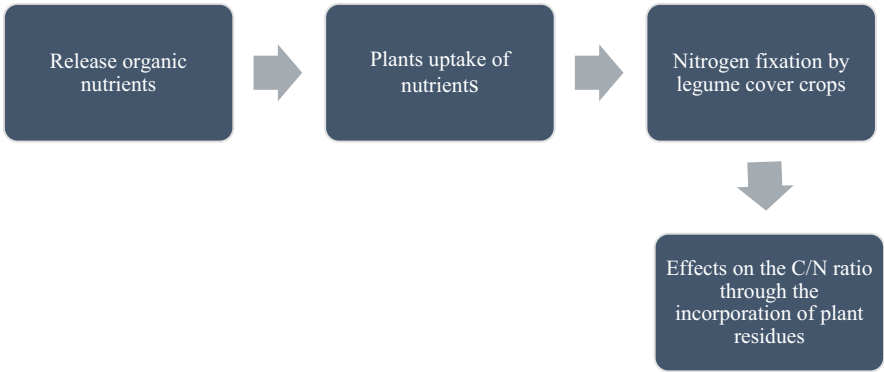


Fig. 2 Direct effects of cover crops on the soil nutritional status

health and productivity on marginal lands. Farmers can reap numerous benefits by selecting appropriate cover crops and carefully managing their rotations, including increased crop yields, lower costs, and improved environmental sustainability.

While there are some challenges and limitations to covering cropping, the potential benefits make it an appealing option for farmers looking to improve their bottom line while caring for the land.

6 Intercropping

The majority of developing countries rely heavily on agriculture, yet as populations rise, cities grow, and industrialization progresses, less land is available for farming due to its non-agricultural uses (Maitra et al. 2021). Depending on the situation, implementing high-intensity cropping systems, such as intercropping, may be a practical way to boost agricultural productivity and overall output (Maitra et al. 2021). Intercropping gives farmers access to a greater range of crops to harvest, which helps farmers fight food and nutrition poverty and diversify household food baskets. Intercropping is growing two or more crops concurrently on the same field for sufficient time to cover the vegetative stage (Gebbru, 2015). Dwivedi et al. found that growing two or more crops can boost productivity per hectare, be more sustainable, and support soil health. Intercropping is associated with farming techniques like double cropping and mixed cropping, allowing for more effective use of resources on the farm and sustainable crop output (Maitra et al. 2021). Intercropping can also be used on marginal land areas unsuitable for conventional agriculture due to poor soil quality or other factors. Intercropping can help improve soil health and fertility by planting various crops with different root structures and nutrient requirements, allowing crops to be grown on otherwise unusable land. However, depending on the intended goal, the selected crops can be arranged into several intercropping systems such as (1) row intercropping (separated regular rows), (2) mixed cropping (without using any row and spatial configuration), (3) strip cropping (several rows of a crop species in separate adjacent rows/strips) and (4) relay cropping system (planting the component at mind stage major crop life cycle) (Ajal 2021; Ebbisa 2022). These farming systems often consist of one or more companion crops in addition to the main crop, which is the most important for economic or food production reasons (Lithourgidis et al. 2011; Maitra et al. 2021). The success or failure of the selected intercropping system enormously relies upon the choice of crops in a combination (Panda et al. 2020). Due to that, under an ideal crop combination, the corresponding and synergistic impact of intercropping is reflected in improved yield and economic benefits (Panda et al. 2020). In addition, a variety of metrics, including purely agronomic ones like yield performance and Land Equivalent Ratios (LER), as well as financial profit returns and risk assessments, can be used to evaluate the advantages and disadvantages of intercropping systems in comparison to the cultivation of a single crop (Weih et al. 2022). This evaluation method will ensure that if the intercropping system is chosen with proper prerequisites, the yield output appears higher than the pure stands of individual crops (Maitra et al. 2021). Figure 3 illustrates intercropping a leguminous crop (cowpea: *Vigna unguiculata*) with a cereal crop (maize: *Zea mays*). Cowpeas can offer affordable symbiotic nitrogen as



Fig. 3 Cowpea (*Vigna unguiculata*) and maize (*Zea mays*) intercropped at smallholder farmers' fields (image by Dr Alphonsus Belane)

a biofertilizer to improve soil fertility in cropping systems, just like most N_2 -fixing legumes. Implementing sustainable methods like intercropping is necessary to boost agricultural output and increase resource use efficiency due to the changing climate (temperature, rainfall, etc.) (Gebru 2015). Through the participatory on-farm technique, smallholder farmers can start using intercropping. The practice of intercropping is recommended for use due to the advantages of biological nitrogen fixation and N benefit for the succeeding crop. Farmers can turn unproductive areas on marginal lands into thriving agricultural zones using this method. While intercropping has challenges, success stories worldwide show it is a viable and effective solution for sustainable agriculture. Intercropping, with careful planning and management, can help farmers improve their livelihoods while contributing to a more sustainable future.

7 Rainwater Harvesting

Rainwater harvesting is the process of gathering and concentrating runoff for productive uses in dry and semi-arid areas, such as crop, animal, pasture, or tree production, as well as residential water supply (Lee and Kim 2012). It is accepted as a strategy for causing, gathering, storing, and preserving local surface runoff for agricultural uses in dry and semi-arid locations to lessen the consequences of temporary rain shortages (Kiggundu et al. 2018). In many farming systems worldwide,

rainwater harvesting is still a vital technique. The first use of such systems is believed to have originated in Iraq over 5000 years ago, in the Fertile Crescent, where agriculture once started some 8000 BC (Hardan 1975). Rainwater harvesting has the following characteristics: it is commonly practised in arid and semi-arid regions, where surface runoff often has an intermittent character; it is based on the utilization of runoff and requires a runoff-producing area and a runoff-receiving area; because of the intermittent nature of runoff events, water storage is an integral part of the system, and it can be done directly in the soil profile or small reservoirs, tanks and aquifers (Biazin et al. 2012). Rainwater harvesting in crop production systems consists of a catchment region for creating runoff and a cropping area for using that runoff. According to the distance and size disparities between the catchment and cropping areas, its significant categories are divided into the following groups: (1) External (macro) catchment rainwater collection; for this application, the catchment area ranges from 1000 m² to 200 ha. The ratio between the catchment area and the cropping area ranges from 10:1 to 100:1, with the catchment area being located outside the arable area; (2) in-situ rainwater harvesting—this method is often referred to as soil-water conservation, as it involves the use of practices that increase the amount of water stored in the soil profile by trapping or holding the rain where it falls.

In this application, there is no separation between the runoff collection area and its storage area; the water is collected and stored where it will be utilized. Internal and (3) micro-catchment rainwater harvesting involves storing runoff for consumptive use in the root zone of a nearby cropping area after collecting it across a flow distance of less than 30 m from a runoff-producing location. In this application, the ratio catchment: cropping area usually varies from 1:1 to 3:1 (Critchley and Siegert 1991; Mzirai and Tumbo 2010). A study conducted in two arid regions of Tanzania (Masika and Vuli, with long-term rainfall averages of 119 and 227 mm, respectively) revealed the great potential of the macro-catchment rainwater harvesting method to improve maize yields (Mzirai and Tumbo 2010). Several maize-cropped fields, influenced by soil water supply, were monitored for their productivity during two experimental seasons (Table 2). Variations in the amount of runoff received per irrigated field were mainly due to field locations in relation to the water source (gully). Maize grain yields were generally positively correlated to the amount of runoff received, while water use efficiency was increased mainly under relatively low amounts of runoff received. This demonstrates crop tolerance and adaptability to the low water supply. In addition, the results show that increased maize water use efficiency can be achieved in relatively dry rainfall areas/seasons. These findings corroborate those reported by Lubajo and Karuku (2021), who found increased water use efficiency of maize by irrigating the crop at a 50% water deficit. The authors explained that maize is amongst several crops which benefit from the reduced soil water supply in exchange for an acceptable yield reduction, which can be economically tolerable compared with the cost value of water saved in water-limited environments.

In another study, El Naim et al. (2018) investigated the performance of in-situ rainwater harvesting (terraces ties technique) on various cultivars of sorghum

Table 2 Potential of the macro-catchment rainwater harvesting technique to improve maize crop productivity in rainfed agriculture (Mzirai and Tumbo 2010)

Field	Runoff received (mm)	Maize grain yield (ton/ha)	Water use efficiency (kg/ha/mm)
<i>Masika—2004</i>			
1	0	0.2	1.1
2	79	1.5	16.5
3	209	2.2	9.6
4	312	3.8	11.5
<i>Vuli—2004/05</i>			
1	0	0.5	1.9
2	320	3.5	9.4
3	345	5.3	13.8
4	251	3.4	11.7
<i>Masika—2005</i>			
1	0	0.3	1.5
2	136	1.7	10.3
3	180	3	15
4	127	2.5	17.3

Table 3 Performance evaluation of the in-situ rainwater harvesting technique for growth and yield parameters of sorghum (El Naim et al. 2018)

Treatment	Growth parameters		
	Plant height (cm)	Stem diameter (cm)	No. of nodes/plant
Terrace ties	126.6–155.1	1.2–1.5	
Conventional ploughing	103.7–128.7	1.0–1.2	
	Yield parameters		
	Panicle weight (g)	No. of seeds per panicle	Seed yield (ton/ha)
Terrace ties	41.1–51.1	1521.6–1570.0	3.2–4.1
Conventional ploughing	28.5	1009.4–1111.7	2.2–2.3

cultivated in a semi-arid area of China, with annual rainfall amounts between 200 and 500 mm. On average, in-situ rainwater harvesting noticeably increased sorghum growth (plant height, stem diameter, number of nodes per plant) and yield parameters (panicle length, width and weight, and the number and weight of seeds), as shown in Table 3. The increase in growth parameters of sorghum under the in-situ rainwater harvesting cultivation indicates that the vegetative growth stage of the crop is directly proportional to the available soil water content and consumptive crop water use. A similar positive effect of in-situ rainwater harvesting was observed in terms of sorghum yield parameters, which agrees with the findings reported by Elamin (2010), who reported significantly higher soil water storage capacity and grain yield (up to 43% for semi-circular, 33% for terrace and 32% for L shaped techniques) compared to the flat (control) treatment.

The lack of infrastructure and technical expertise is one of the most significant challenges of rainwater harvesting on marginal lands. Many farmers may lack the necessary equipment or knowledge to install rainwater harvesting systems. The variability of rainfall patterns is another issue. Rainfall can be unpredictable in some areas, making it difficult to plan and manage rainwater harvesting systems effectively. Despite the challenges, numerous examples of successful rainwater harvesting on marginal lands exist. For example, the Tarun Bharat Sangh organization has installed rainwater harvesting systems on over 1000 ha of marginal land in India. The Tigray region of Ethiopia has implemented a community-based rainwater harvesting program that has increased food security and reduced poverty levels (Wubetu 2016). Rainwater harvesting on marginal lands has many advantages, including increased water availability, improved soil quality, and economic opportunities for farmers, and it can be a viable solution for sustainable agriculture and water resource management.

8 Incorporating Mulches for the Restoration of Marginal Lands

Marginal lands are areas that are being, or are being planned to be, replanted with vegetation but where the soil qualities are such that they would not support typical vegetative development over time. Using mulch on marginal lands can protect the soil from wind and water erosion, and reduce soil compaction, which can negatively impact crop roots and impede plant growth and development. While crops are in their early and intermediate stages of growth, covering the soil's surface with various organic and inorganic mulch materials might help to reduce water loss. Mulching is one such approach that conserves soil moisture, suppresses weed growth, improves soil structure and temperature, improves soil micro-organisms, and, thus, increases plant growth and yield (Kader et al. 2017). Furthermore, a mulch sustains the fertility of the soil, protects the soil from water and wind erosion, preserves the soil moisture, protects the plant from the attack of insect-pest and diseases, moderates the soil thermal regime throughout the cropping season, and increases overall crop production (Maitra et al. 2021; Kader et al. 2017). Mulches are either organic or inorganic (Zhang et al. 2020). Organic mulch can be made using grass, straw, dry litter, bark, sawdust, and compost, and these are easily degradable and contribute organic matter and nutrients to soils (Zhang et al. 2020). On the other hand, inorganic mulch material includes plastic (polyethylene and gravel, pebbles, and crushed stones), widely used on dryland fruit crops. When used in cropping fields, both types of mulch have multiple benefits related to improved soils' physical, chemical, and biological properties (Mgolozeli et al. 2020; Steinmetz et al. 2016). Figure 4 shows seedless grass mulch adopted as part of climate-smart practices by smallholder farmers in Limpopo province (Vhembe and Capricorn district), South Africa. The smallholder farmers in the Vhembe district incorporate mulch into the soil to

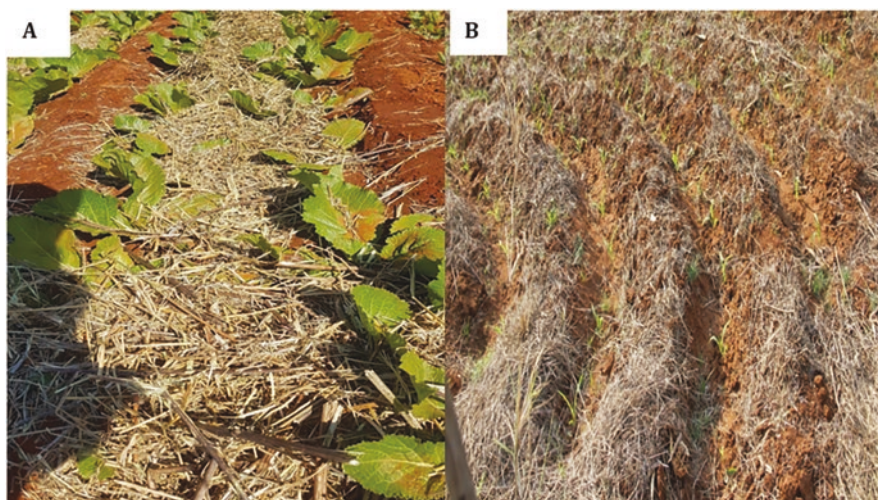


Fig. 4 Mustard spinach mulched with seedless grass (a) and soil incorporated with grass (b) (image by ARC-VIMP)

realize the benefits, while in the Capricorn district, mustard spinach is mulched with grass (Fig. 4a). Many studies demonstrate the value of synthetic mulches, including plastic film sheets, in preserving the moisture content of the soil. Such articles could promote the plastic sheet industry and open investment prospects in nations with dry and semi-arid climates (Alsamin et al. 2022). Smallholder farmers in the Vhembe district practice contour farming with mulching in slopy gradient fields to minimize soil erosion (Fig. 4b).

9 Reclamation of Marginal Lands Through Biostimulant Applications

According to estimates, the world's population is currently 8 billion, will be 8.5 billion in 2030, and will reach 9.7 billion in 2050 and 10.4 billion in 2100 (United Nations 2022). Although the challenges of declining arable land owing to land degradation, among other things, are also increasing, the ever-increasing population's need for food is significantly increased (Karapouloutidou and Gasparatos 2019; Othibeng et al. 2022). As a result, agriculture must develop environmentally friendly and sustainable production methods to meet the difficulties of rising global food demand, declining arable land and resource availability due to growing environmental awareness, and the overall effects of climate change (Ngoroyemoto et al. 2020; Karapouloutidou and Gasparatos 2019). Marginal soils are also a result of decreasing soil moisture conditions brought on by climate change. For instance, drought conditions are predicted to cut agricultural productivity by 50% in 2050 and

90% in 2100. One of the many agricultural strategies that can improve soil's physical, chemical, and biological qualities and restore the fertility of deteriorated soils is adding soil amendments using biostimulants (Karapouloutidou and Gasparatos 2019). According to reports, biostimulants can improve nutrient uptake while reducing the impacts of abiotic stress on plants, such as salinity, nitrogen deficiencies, and other stressors, including drought (Kaloizoumis et al. 2021). The impact can be attributed to the biostimulants active ingredients, including polysaccharides, proteins, amino acids, and glycosides (Baltazar et al. 2021). Biostimulants can also improve crop growth in soilless production, which can be a viable option for marginal soils unsuitable for crop production (Fig. 5).



Fig. 5 Pepper growth difference between treatment with and without Paclobutrazol under a soil-less hydroponics production system (image by ARC-VIMP)

10 Biostimulant Application Effect on Chemical and Physical Properties of Marginal Soils

Karapouloutidou and Gasparatos (2019) investigated the impact of two commercial products on the chemical characteristics and nutrient availability of calcareous saline-sodic soils: the biostimulant Active and the organic soil amendment Correal Plus. The soil amendment product is an organic chemical complex used to reclaim saline-sodic soils, whereas the biostimulant is a seaweed extract with significant components like kahydrin, alginic acid, and betaine (Karapouloutidou and Gasparatos 2019). The results showed that an increase in the application of Correal Plus, from a rate of 10 to 50 L/ha, significantly decreased the soil pH of saline soils (Karapouloutidou and Gasparatos 2019). The result was attributed to the product's acidic composition and the H^+ ions generated during nitrification (Karapouloutidou and Gasparatos 2019). The non-significant effect at lower concentrations of Correal Plus could be due to the $CaCO_3$ content of the soil. On sandy and clay loam soils, a rhizogenic biostimulant containing fulvic acids, calcium, calcium lignosulfonate, prebiotic- and probiotic molecules considerably decreased the soil pH, enhancing the uptake and availability of Ca, Mg, K, and P (Yousfi et al. 2021). Rhizogenic biostimulant use and low quantities of Correal Plus application had different effects on soil pH, which might be attributed to the soil's state and the products' Ca contents (Karapouloutidou and Gasparatos 2019; Yousfi et al. 2021). Electrical conductivity and soil pH can restrict soil productivity for some crops, influencing the availability and uptake of various plant nutrients. Electrical conductivity and soil pH can restrict soil productivity for some crops, influencing the availability and uptake of various plant nutrients. Salinity is thought to be primarily caused by the Na ions, with small contributions from Cl, Mg, SO, and HCO_3 (Ahmad et al. 2022). The exchangeable Na content of soils treated with Actiwave was considerably lower in the lowest concentration than the control, and it was not statistically different in the highest concentration (Karapouloutidou and Gasparatos 2019).

The application of microbial biostimulants significantly increased the N, P, K, and soil organic matter content. Microbial biostimulants can stimulate the breakdown and mineralization of soil organic matter, improving soil nitrogen availability (Yousfi et al. 2021). Mukherjee et al. (2022) used combinations of microbial inoculant strains (*Enterobacter hormaechei* strain BHUJPCS-15, *Brevundimonas naejangsensis* strain). The soil organic matter content of sodic-saline soil was increased with an increase in Actiwave concentration, while it decreased with an increase in Correal Plus concentration (Karapouloutidou and Gasparatos 2019). Improving soil organic matter content is essential for soil fertility, regulating the soil's physical properties and nutrient balances of the soil matrix (Yousfi et al. 2021). Correal Plus application significantly reduced soil P content, which is attributed to the significant amounts of Ca in the product, which binds P into an insoluble form (Karapouloutidou and Gasparatos 2019).

11 Biostimulant Application Effects on Soil Microbiology of Marginal Soils

Several plant-beneficial microbes and biostimulant products have been tested to improve soil contaminated with heavy metals like Cu, Cd, and Pb by producing proteins that immobilize or adsorb them into the chitin of their cell walls and chelate them in their cells (Alengebawry et al. 2021). The aim is to restore soil fertility by improving the soil biological properties. For example, bacteria containing biostimulants BNPIII (various nitrogen-fixing bacteria) and Azzofof (IAA, acc-deaminase, nitrogenase, and phosphomonoesterase) were tested on marginal soils, and they were found to have a positive effect on soil microbial populations (Widawati and Suliasih 2021). The application of a rhizogenic biostimulant by Yousfi et al. (2021) significantly (two- to threefold) improved the soil microbial activity and enzyme activity, especially the catalase, dehydrogenase, and phosphatase activities, in sandy soils. This could be attributed to the positive effect of the biostimulant on soil organic matter content or input of organic substrates and the pre- and probiotics, which are known to promote the growth of soil microorganisms and enzyme synthesis within a soil-plant system (Yousfi et al. 2021). Waguespack et al. (2022) recorded increased soil microbial activity using a blackstrap molasses solution as an organic biostimulant. Furthermore, combining compost fertilization and a *Trichoderma*-based biostimulant significantly stimulated nitrogen-fixing and ammonia-oxidizing bacteria in the soil (Alengebawry et al. 2021). Variations in the effect of biostimulants on soil properties are reported, and this could be due to differences in the soils, thus there is a need to test soils before applying biostimulants to understand the texture, availability, and nutrient content in the soil for appropriate biostimulant applications (Yousfi et al. 2021).

12 Integrated Pest and Disease Management

Pests and diseases are one of the world's leading threats to food security, particularly for agronomic crops and the world's dominant food crops (Khan et al. 2019). Due to that, disease and pest infestations cause significant plant damage, affecting the yield, quality, and economic value of various crops (Zijlstra et al. 2011). There is a claim of the possible yield losses: diseases account for 16%, storage losses account for 14%, and pests account for 36% (Mutondwa 2018). This is a significant loss, particularly regarding food security, because crop losses to pests and diseases may represent the equivalent of food required to feed over one billion people (Pretty and Bharucha 2015). Although pesticide-based methods have been used for a long time to manage pests and diseases in agriculture, their continued use is linked to unfavourable impacts on the environment, on- and off-field effects on organisms that aren't intended targets and may even be harmful to farmers' health (Barzman

et al. 2015; Pretty and Bharucha 2015; Kumar et al. 2019; Van der Werf and Bianchi 2022). Growing awareness of the harmful effects of the indiscriminate use of chemical pesticides has sparked a widespread adoption of more eco-friendly and affordable methods to ensure global food security for future generations (Khan et al. 2019; Roberts et al. 2020). In order to fully utilize pesticides in conjunction with biological, physical, and cultural control approaches, integrated pest and disease management programs have been acknowledged as one of the most effective strategies for reducing or avoiding the severity of the problem (Fouad et al. 2019).

Kansiime et al. (2017) defined Integrated Pest Management (IPM) as the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep plant protection products and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. These strategies include site selection and preparation, utilizing resistant cultivars, altering planting practices, modifying the environment by drainage, irrigation, pruning, thinning, shading, and applying pesticides if necessary (Pandey et al. 2016). According to Munyuli et al. (2017), implementing an effective IPM-integrated program requires knowledge of pest awareness, monitoring, and inspection, as stipulated in Fig. 5. The integrated strategies are used to eradicate pests and diseases, manage them below economically dangerous levels at low numbers, and select and apply appropriate control measures (Green et al. 2020). Observation is the most crucial task in integrated pest management (Green et al. 2020). Which pests are dangerous to what crops and when? Where are they from? How do they procreate? What can be done to stop them from arriving? These things may be comprehended, and by doing so, the insect's life cycle can be disrupted to stop it from developing into a pest. The importance of schematic representation in Fig. 5 of essential factors to consider in integrated pest management. Every integrated program's efficiency revolves around four important principles (Khan et al. 2019).

The first principle is appropriately identifying pests, natural enemies, and diseases (George et al. 2011). As a result, not all pests and other living organisms need to be controlled because some are either harmless or useful for crops with significant economic value (Khan et al. 2019). Early detection could also help farmers prevent costly errors in terms of time and money by enabling them to take appropriate measures rather than applying the incorrect product that doesn't control the intended organism or illness (Zijlstra et al. 2011). For instance, if a plant is damaged by over-watering, it can be mistaken for a fungal illness because many fungal and viral infections grow in moist environments (Zijlstra et al. 2011).

Monitoring should determine the likelihood of a pest or disease before it affects the cultivated crops when the pests and illnesses have been accurately recognized (Zijlstra et al. 2011; George et al. 2011). Scouting should be used to identify before, during, and after the growth period as it would help identify the area and time that efforts are required (Zijlstra et al. 2011). Implementing the IPM approach seeks to determine the permissible levels of pests and diseases and take control when those levels are exceeded, mainly before they result in a financial loss (George et al.

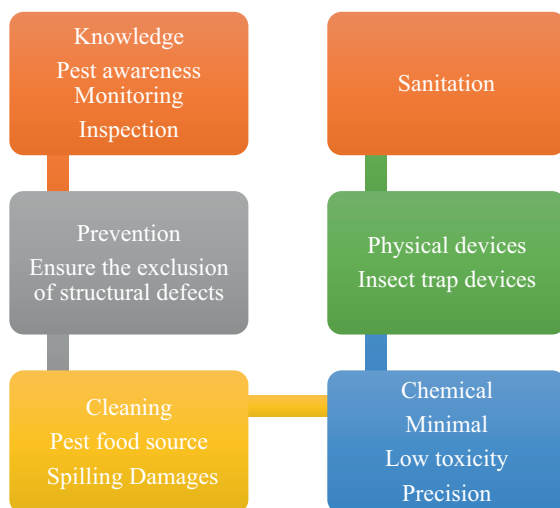
2011). It is imperative to stop the pest or disease from developing a resistance to any chemicals produced by the plant or used on the crops. The most appropriate management measure should be chosen when proper identification, monitoring, and acceptable threshold action levels of a pest or disease have been attained (George et al. 2011; Khan et al. 2019). Lastly, documentation of the data collected would be able to provide knowledge or warning to farmers and other agricultural stakeholders (Sciarretta and Calabrese 2019).

13 Weed Management

Growers constantly fight weed control within the agricultural production systems in different regions as it poses a danger to producing profitable crops. Together with pathogens like fungi, bacteria and pests, which damage crop plants and negatively affect the economy, the environment, and society, weeds generally impede crop growth and provide the greatest threat to crop yield losses (Oerke 2006). Globally, crop yield losses due to weeds are reported to be up to 40% annually. Without any control, a 100% yield loss could be predicted (Milberg and Hallgren 2004). Weeds compromise crop productivity by competing for sunlight, water, nutrients, and space. The economic risks of weeds, apart from the loss of agricultural crop production and yields, are the increased production costs (weed control) and their interference with the harvested produce (contamination), resulting in diminished product quality. Weeds must be eliminated from a field before horticultural crops are planted and continuously eliminated throughout the growing season to produce optimal yields. Various weed species can reduce productivity, and the losses vary depending on how well-adapted a crop is to compete with weeds. According to Hossain and Begum (2015), the infestation of weed species in crop fields generally depends on crop species, cropping systems, management practices, environmental conditions, seasonal variation, and soil (type, properties, nutrients, and moisture content). For instance, whole-grain legumes like peas compete poorly with weeds in the early growth phases, and barley and rye are typically more competitive than wheat (Corre-Hellou et al. 2011). Yield losses in crops due to weeds also depend on several factors, such as weed emergence time, weed density, type of weeds, and crops (Sharma et al. 2021). Thus, developing a weed management program and understanding weed biology and ecology is critical to developing effective management practices that produce profitable crop production.

Chauhan (2020) emphasizes that applying integrated weed management using different but complementary techniques within a system is crucial instead of relying on a single technique. Some of the factors that contribute to the vicious cycle of weeds are presented in Fig. 6, stipulating the weed management challenges, particularly for marginal fields of smallholder farmers. This is because smallholder farmers are vulnerable and can get trapped in a vicious weed cycle associated with low income, labour shortage, and migration, as shown in Fig. 6. The vicious weed cycle

Fig. 6 Important factors for integrated pest and disease management (adopted from Khan et al. 2019)



(Figs. 7 and 8) is genuine in most marginal lands because, unlike insect and disease outbreaks, weeds grow in a field essentially continuously from year to year (Vissoh et al. 2004). In addition, weeds compete with crops for the same resources as crops: nutrients, carbon dioxide, light, and water (Sims et al. 2018). The main challenge in agricultural weed controls is developing one less risky technique that is less costly, highly effective, with less labour, and much quicker.

Using herbicides before, during, or after planting, before the crop emerges (pre-emergence), or during, during, or after the crop emerges (post-emergence) to control weeds germinating from seeds is an available weed management method. However, for pre-emergence herbicides to break down and become active in a soil water solution and be absorbed by emerging weeds, rainfall or irrigation water must fall within the first 2 weeks of application (Buhler 1999). Furthermore, exposure to high soil temperatures encourages germination and early weed development, minimizing the time the weed is exposed to pre-emergence herbicides. There are a wide variety of commercially available herbicides and herbicide formulations. The selection is primarily influenced by several variables, such as the soil type, crop rotation program, weed species to be managed, and tillage techniques. Unfortunately, the extensive use of herbicides may lead to crop damage (Sharma et al. 2014), soil infertility, soil acidification, and contamination of natural resources such as groundwater due to potential leaching (Meng et al. 2016). Many pesticides negatively affect the ecosystem's sustainability and health (Meng et al. 2016). According to Gaupp-Berghausen et al. (2015), microbial communities have declined. The ongoing effects of weed control can lower soil biodiversity and nutrient availability, costing farmers annually. Weeds develop herbicide resistance due to the ongoing use of chemical herbicides for selective weed control, endangering world health and food security (Hicks et al. 2018). Also, it's essential to consider the herbicide's weed range, weed sizes, crop safety, residual activity, and cost (MacLaren et al., 2020).

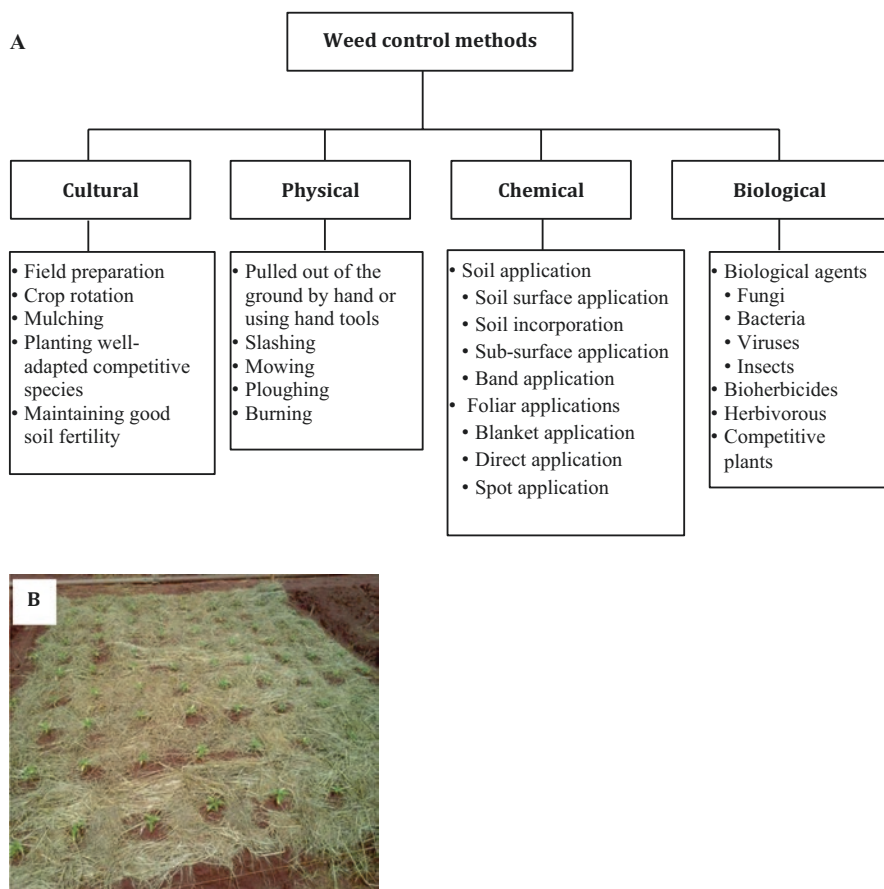


Fig. 7 Adopted weed control methods (a) and local grass mulch being used as a cultural method in controlling weeds on amaranth production in the semi-arid area of Roodeplaat, Pretoria (b) (image by ARC-VIMP)

The biocontrol technique is another method that has proven effective in managing invasive weeds in uninterrupted sites such as natural areas, forests, and wastelands. However, this method is unsuitable for controlling weeds in agricultural lands disturbed by other management practices and cropping cycles. The use of RNA to silence crucial weed genes by RNA interference (RNAi), which either increases weed susceptibility to herbicides or results in weed death, is a promising new weed control approach. The use of RNA as a spray has a lot of potential for controlling weeds, and the sequences can be created only to target weed species (Westwood et al. 2017).

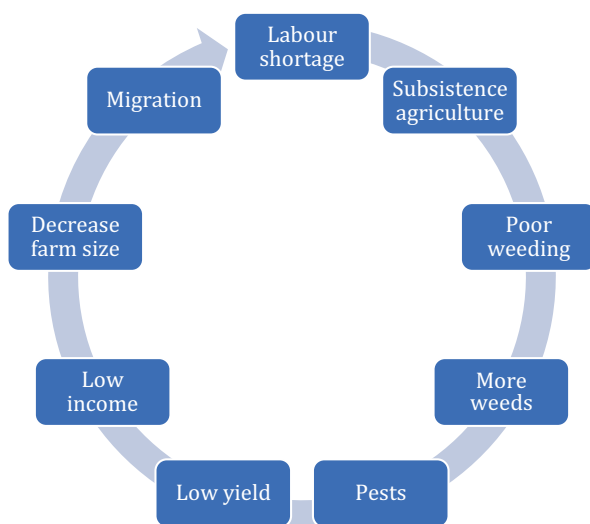


Fig. 8 Vicious weed circle (adopted from Vissoh et al. 2004)

14 Conclusions

The documented information in this chapter demonstrates the potential and promotion of low-input agricultural practices to improve marginal lands for sustainable crop production and food security. The emerging picture of different agricultural practices and sustainable capability can form viable cropping systems on marginal agricultural lands under specific climatic conditions in enhancing crop productivity. The set of agricultural practices, such as conservation agriculture, crop rotation, and cover cropping, is intended to integrate and facilitate improved nutrient uptake through different mechanisms for marginal soils. In addition to the relevance of sustainable production practices, their potential impact arguably lies in their functional ability to ensure sustainable productivity without affecting crop yield. However, targeting the most effective agricultural practices for specific crops under specific conditions is imperative.

Moreover, increasing awareness and empowerment of farmers, including resource-poor farmers, on using and adopting low-input agricultural practices will sustainably improve crop productivity and food quality. The benefits associated with sustainable agricultural practices for crop performance, soil health improvement through cover cropping, and stimulating the uptake of nutrients indicate the potential for improved crop productivity. Further investigations for low-input agricultural practices are required to investigate their sustainability and climate change effects on marginal agricultural lands.

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Remediation Strategies That Can Be Adopted to Reclaim Degraded Soils in the Communal Areas of Zimbabwe



Cosmas Parwada and Justin Chipomho

1 Introduction

Soil degradation is one of the most serious and widespread environmental problems on a global scale (Parwada et al. 2020; Boardman 2006). Soil degradation describes loss of intrinsic physico-chemical and/or biological properties of soil either by natural or anthropic processes, which result in the diminution or annihilation of important ecosystem functions (Baumhardt et al. 2015). Virtually almost (>90%) all soils in the world have undergone transformations due to human action, which has diminished their quality and their ability to provide services, both to ourselves and to the ecosystems. The soil is a dynamic structure that is in constant formation and degradation, and it is an extremely thin layer that supports life. It is where a large part of plant species is found, most of the processes of conversion of organic into inorganic matter takes place and where several animal species, fungi and bacteria reside (Nyamangara et al. 2020). Therefore, soils are essential for agriculture and human survival on earth.

Africa's primary past and present concern has been the loss of soil security by nutrient depletion, that is, the decreasing nitrogen, phosphorus and potassium (NPK) levels (kg ha^{-1}) along with micronutrients in cultivated soils (Rodrigo Comino et al. 2017). Unfortunately, there is an exponential growth in population meaning potential starvation and migrations in Africa (FAO 2019). Intensification of land use to meet the increased food demands combined with the mismanagement of the land leads to the degradation of the continental soils. This poses the ultimate

C. Parwada (✉)

Tugwi Mukosi Multidisciplinary Research Institute (TMMRI), Midlands State University, Zvishavane, Zimbabwe

J. Chipomho

Department of Crop Science, Faculty of Plant and Animal Sciences and Technology, Marondera University of Agricultural Sciences and Technology, Marondera, Zimbabwe

question of how the appropriate sustainable technologies that will permit increased productivity of soils can be identified. It has been estimated that due to desertification and soil erosion, the productivity of some lands has declined by 50% (Baumhardt et al. 2015). For instance, in African countries, the yield reduction due to previous soil erosion ranges from 2 to 40%, with an average loss of 8.2% for the whole continent (Le Roux et al. 2007; Li et al. 2018). This risks the food security in the continent as little food is produced from the degraded soils. According to different sources, figures about agricultural land degradation varied from 15 to 80% during the last two decades (Rodrigo Comino et al. 2017; FAO 2019). Some recent estimates described the agricultural lands to be about 25% highly degraded, 44% slightly to moderately degraded, and only 8% being improved (Baumhardt et al. 2015; FAO 2019). Le Roux et al. (2007) reported that dry lands are more prone to degradation which cover about 40% of the earth's land area and is related to the livelihood of 2.5 billion populations. Boardman (2006) reported that about 16% of the agricultural land reduces its yield due to soil erosion.

It has been reported that most of the productive agricultural land in the world is already in cultivation (Pimentel and Burgess 2013). Another challenge that is impacting agricultural land is desertification, which is increased by poor land management practices such as deforestation, overgrazing, improper irrigation practices, over-cropping or other factors where soil health and soil biology is significantly impacted, and soils are degraded. Therefore, soil degradation can be defined as human-induced deterioration of its quality, which means the partial or entire loss of one or more functions of soil (Li et al. 2018; Lai and Singh 1998). Deteriorating soil structure during soil erosion contributes to diminished productivity in at least two important ways that is; decreased infiltration and storage of available water and impaired root exploitation of the soil. Lower organic matter and higher clay contents associated with erosion make soil more susceptible to compaction. If it does not actually decrease the available water holding capacity of the soil, compaction reduces infiltration and restricts plant root growth. Both decrease the water-supplying capacity of the soil and diminish the soil's yield capacity.

Erosion decreases the soil's water-supply capacity and this further decreases the soil productivity in the communal areas of Zimbabwe. Accelerated soil erosion, due in part to growing pressures on the land from human and livestock populations, is especially common in peasant farming areas. The accelerated erosion removes soil from the surface much more rapidly when the soil profile deepens. Thus, the rooting depth of crops rapidly decreases in soils that are shallow to a root-restricting layer such as a bedrock or hardpans (Rodrigo Comino et al. 2017). The erosion exacerbates the problem of low soil organic matter (SOM) content in the smallholder farming communal areas in Zimbabwe. Moreover, the organic matter of the soil is reduced, which may result in negative effects concerning its quality, thus leading to loss of productive capacity and reduced productivity. Soils in the communal areas of Zimbabwe are characteristically low (<2%) in soil organic carbon leading to poor structure as well as poor water-holding and nutrient holding capacities. The loss of SOM by erosion causes a disproportionate loss of several plant nutrients thereby reducing the soil productivity. Organic matter is the most abundant indigenous

source of N and some secondary nutrients and micronutrients, especially in strongly weathered soils. Generally, eroded soils have higher acidity and lime requirement than uneroded soils and this has further reduced the crop productivity in these soils.

The land degradation affects large parts of Zimbabwe and mainly in communal areas where annual soil loss averages $3.3 \text{ t ha}^{-1} \text{ year}^{-1}$ (Nyamangara et al. 2020). Soil loss in the commercial areas averages $0.6 \text{ t ha}^{-1} \text{ year}^{-1}$ (Le Roux et al. 2008). The most obvious impact of land degradation is the degradation of thousands of hectares of the country's arable lands and rangelands. Arable land size is shrinking in Zimbabwe, and several anthropic activities, such as soil degradation and deforestation etc. lead to further reduction of this land. Soil can degrade without actually eroding. It can lose its nutrients and soil biota and can become damaged by water-logging and compaction (Baumhardt et al. 2015). Erosion is only the most visible part of degradation, where the forces of gravity, water flow, or wind actively remove soil particles (Parwada and Van Tol 2018). FAO (2019) estimated soil loss in rangelands ranges from 3 to $75 \text{ t ha}^{-1} \text{ year}^{-1}$, with generally high rates in the communal lands. The soil loss from communal arable lands ranges from 15 to $50 \text{ t ha}^{-1} \text{ year}^{-1}$. The main causes of such high rates in the communal areas are attributed to land pressure and deforestation. Wood fuel is the main source of energy used in rural Zimbabwe and provides 61% of total energy supply and this aggravates the deforestation and land degradation (Parwada et al. 2020). Therefore, more efforts should be put on rehabilitating degraded soils in farmland in order to increase crop productivity. However, the rate of soil degradation is site specific which depends on the soil type, slope, plant cover and land use in a particular area. Hence, soil rehabilitation strategies should be developed considering these specific conditions if they are to be successful. Therefore, this chapter looked at the status of soil degradation and explored possible strategies to reclaim the degraded soils in the communal farmlands of Zimbabwe.

2 Indicators of Soil Degradation in the Communal Areas of Zimbabwe

The severity of soil degradation depends on the initial status of the land, the magnitude of drivers that place pressure on land, the responses of the land system, and the impact of feedback from these responses on land resources (Parwada et al. 2020). The indicators of soil degradation can be visual, physical, chemical, biological, and integrative (Rodrigo Comino et al. 2017). The soil can lose certain physical, chemical or biological qualities that underpin the web of life within it. Organic and inorganic solids, liquids of different types and gases in intimate contact with the solid phase comprise the three-phase system that is soil (Nyamangara et al. 2020). Hence soil management should include management of all the three phases but with an emphasis on the solid and liquid phases. Physical degradation of soil most often reflects a change in the total volume or size distribution of the pores brought about

by reorganization of the solid phase. Physical indicators can be measured by analysing the arrangement of the solid fractions (coarse and fine) of the soil (Lai 2000). These manifest themselves, for example, as plant growth limitation, horizon thickness, textural gradient, permeability, porosity, density, penetration resistance, aggregate stability infiltration, surface runoff, compaction, entrapment, temperature, and plasma-skeletal disjunction of the soil. Due to erosion of various forms, soils in the communal areas of Zimbabwe are characteristically of shallow soils with low nutrient and water holding capacity. Therefore, there is limited crop productivity making the farmers vulnerable to food crisis for the most parts of the year.

Chemical degradation refers to the accumulation of toxic chemicals and chemical processes which impact on chemical properties that regulate life processes in the soil (Corwin et al. 2007). Li et al. (2018) stipulates that a change in one or more of these soil chemical properties have a direct and indirect adverse effect on the chemical fertility of soils. Chemically degraded soils have the presence of large amounts of toxic chemicals interfering with activities of soil life processes. These toxic chemicals may also interfere with nutrient availability, nutrient uptake and nutrient element mobility. Overlooking of chemical soil degradation has been due to the fact that its impact is not clearly visible from the onset. Chemical indicators can be measured by monitoring soil pH, salinity, organic matter content, cation and anion exchange capacity, nutrient cycling, and the presence of toxic or radioactive elements, while biological indicators may include measures of the presence of macro- and microorganisms, as well as their activities and by-products (FAO 2019).

Very small proportion (<35%) of Zimbabwean soils are found to be with pH between 5 and 6 but the majority are very acidic (pH < 4.5) for most sandy soils (Nyamangara et al. 2020). The increase in acidification of the soils may be attributed to four main causes: decrease in the use of manure, virtually no use of lime, increasing use of acidifying chemical fertilizers and leaching (Gafur et al. 2000). Because when the soil pH is less than 6, the availability of Fe, Mn, Cu, Zn and other elements will be activated, leading to the accumulation of heavy metals in crops, thereby affecting human health. In the strongly acidic soil with pH < 5.5, content of exchangeable Al^{3+} can increase to more than 90% of the cation exchange capacity (CEC). Given that it is easy to free Al^{3+} , this will cause aluminium toxicity and adversely affect the growth and development of crops in these areas. In other cases, a decrease in soil pH will cause leaching of the exchangeable Ca^{2+} , leading to the disintegration of the soil structure, which is difficult to form a granular structure, thus causing soil hardening. The reduction of soil acidity is not suitable for the survival of soil microorganisms (Baumhardt et al. 2015). The most direct manifestation of soil environment deterioration is that it affects the growth and development of plants, reduces crop yield and quality (Li et al. 2018), reducing farmers' income.

Commonly in the once commercial farms, increased soil acidity was due to use of chemical fertilizer. Use of in-organic fertilizers acidifies the soil, and that when a soil becomes more acidic, more fertilizer is needed to maintain the same yield (Pimentel and Burgess 2013). The current smallholder farmers are no longer afforded to buy and apply the in-organic fertilizers hence low crop productivity. When soils becoming more acidic (lower pH values) over time is through the use of

nitrogen (N) fertilizers containing ammonium-N (Le Roux et al. 2007). As the ammonium-N in fertilizers undergoes nitrification (conversion of ammonium to nitrate in soils by bacteria), hydrogen (H^+) is released, which can increase acidity (Nyamangara et al. 2020). As the percentage of ammonium increases in a given fertilizer the acidifying potential will also be increased, thus reducing pH.

The most limiting nutrients in the smallholder crop land is nitrogen and phosphorus. Inadequate nutrient supply and nutrient mining in the communal cropping land has caused high levels of soil degradation in many Zimbabwean soils. The nutrient depletion has resulted in serious nutrient imbalances especially in soils under low-input farming systems in marginal lands of Zimbabwe. Yield reduction and loss of biological diversity of soil due to the presence of certain pollutants are also sources of soil health decline under the definition of soil degradation. Multiple nutrient deficiencies and increased soil acidity have recently been reported in some communal areas. The common deficiencies are of N, P and S but at advanced stages of fertility depletion, deficiencies of Mg and K as well as those of micronutrients such as Zn and Cu also occur (Gafur et al. 2000). The depletion of N, P and K in Zimbabwe's agricultural soils has been estimated at 20–40, 3.5–6.6 and 17–33 kg ha⁻¹ year⁻¹ respectively (Greenland et al. 1994). Liming is needed in order to neutralize soil acidity. Nevertheless, liming is unpopular amongst farmers as manure, as it needs to be applied in large quantities to have an impact. The communal farmers are generally not aware of how important it is to do pH tests and liming their soil resulting to perennial low crop yield. Most of the farmers are conditioned to achieve high crop yield in the faster and easier way through use of inorganic fertilizers (Nyamangara et al. 2020). In this case, the farmers are feeding the crop and not the soil thereby declining in soil quality. Therefore, farmers need to be educated on the importance of building soil health and fertility through integrated soil fertility management practices as well as the importance of soil analysis, among other issues.

Biological degradation of soil as described herein refers to the impairment or elimination of one or more “significant” populations of microorganisms in soil, often with a resulting change in biogeochemical processing within the associated ecosystem (Le Roux et al. 2007). “Significant” microorganisms are those for which an ecologically significant role is understood (Li et al. 2018). Biological soil degradation involves loss of SOM, lowered biodiversity, loss of a soil's ability to store and sequester carbon and release plant nutrients, and the release of greenhouse gases. Parwada et al. (2022) noted that the overall effect of continued soil degradation resulting from land misuse and mismanagement was a steady decrease of soil organic carbon by 0.25% per year under sole cropping systems. Integrative indicators, also called key indicators, are used to assess soil quality and degradation. An integrative indicator should gather basic information about the composition, structure, and functions of the soil system. The objective is to reflect the interactions between different biotic and abiotic processes that express spatiotemporal transformations in the soil system, such as enzymatic activities and aggregation (Rodrigo Comino et al. 2017). This is a very important indicator of soil degradation, unfortunately there is limited research in regard to this aspect among the communal areas of Zimbabwe.

3 Causes of Soil Degradation of Communal Areas of Zimbabwe

Soil erosion survey in Zimbabwe, based on detailed analysis of aerial photographs, indicated that slightly more than 1.8 million hectares of land was degraded by early 1990s (Whitlow 1988). The most extensive and severe erosion occurs within the communal farming areas, where some 83% of the eroded land is located (Nyamangara et al. 2020; Parwada et al. 2022). Zimbabwean soils are predominantly (>65%) alfisols (Fig. 1). Usually the alfisols develop in semi-arid to humid areas and have a clay-enriched subsoil and relatively high native fertility. The entisols which are recent, immature with no or little horizonation occupies about 16% of the Zimbabwean land. Oxisols are also present in the far eastern border and some part of Masvingo province but occupying relatively a small proportion of the land area (Fig. 1). The oxisols are highly weathered soils so that they contain no more than 10% weatherable materials at all depths. These soils have low cation exchange capacity (CEC) and are usually red or yellow in colour because of high concentrations of iron (III) and aluminium oxides and hydroxides.

The utisols occupies about 5% of the land area and are present in geologically old landscape settings. Utisols have a humus-rich surface horizon and a layer of clay that has migrated below the uppermost layer with low nutrient content particularly low in available Ca, Mg, K, and Na. The vertisols occupies about 20% of the

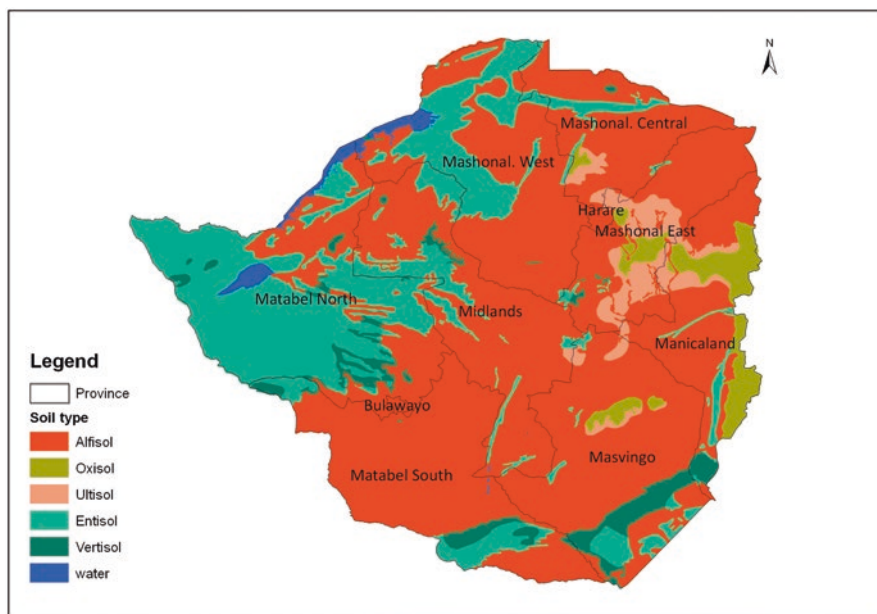


Fig. 1 Map showing the distribution of the major soil types in Zimbabwe (adapted from <https://www.bing.com/images/search?view=detailV2&ccid=EmIua7QU&id=2A64E864BDA>)

Zimbabwean land (Fig. 1). Vertisols have clay-size-particle content of >30% by mass in all horizons of the top 0.50 cm of the soil profile. These soils are dark-coloured and that may also be characterized by salinity and well-defined layers of calcium carbonate (Parwada et al. 2022).

In Zimbabwe, the agricultural mismanagement and deforestation causes 58% and 28% of soil degradation respectively (Zingore et al. 2005). In arid and semi-arid areas, soils lack organic matter and have a low carbon: nitrogen ratio due to negligible plant cover and vegetation. In some desert soils, the amount of organic matter is even less than 1% (Li et al. 2018). The agricultural mismanagement such as poor soil fertility management, poor cropping systems are the main causes of soil degradation together with the rampant clearance of forest. Nutrient depletion due to poor agricultural management and loss of soil fertility is another important issue in the soil degradation process. Poor land preparation such as high frequency of conventional tillage and burning of crop residues have caused rapid soil degradation among the communal areas of Zimbabwe. The land is left bare for the greater part of the winter season thereby exposed to high wind erosion and high heat that harden the soil, limiting water infiltration during the early rains leading to high runoff. Figure 2 shows three main types of soil degradation, causes and their classification.

Studies show that the most (53%) common type of soil degradation in the communal area of Zimbabwe is physical which in turn influences the biological and ecological degradation (Parwada and Van Tol 2018; Li et al. 2018). Chemical soil degradation was observed in areas with heavy use of inorganic fertilizers and use of saline water for irrigation especially irrigation schemes (Lai 2000).

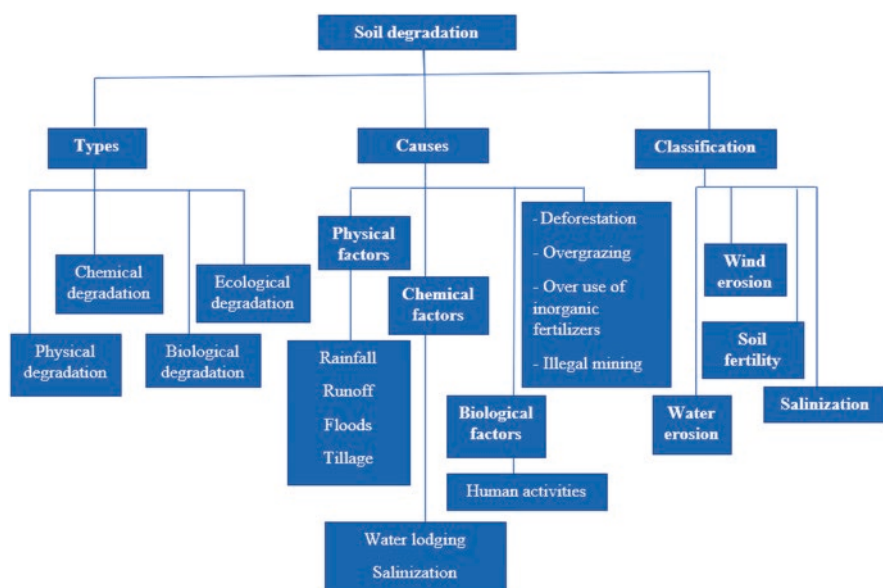


Fig. 2 Schematic representation of the types, causes and classification of soil degradation in Zimbabwe communal areas

Poor and inappropriate land management are the main causes of physical, chemical and biological degradation of cultivated lands, pasture, rangelands and forest lands (Pimentel and Burgess 2013). Causes for soil degradation are many and include decline of soil fertility, development of acidity, salinization, alkalization, deterioration of soil structure, accelerated wind and water erosion, loss of organic matter and biodiversity. Major factors deteriorating the soil quality chemically are salinization, erosion, depletion of nutrients by exhaustive agricultural practices, and contamination with toxic metal ions (Lai 2000). Food security to meet the requirements of the ever-increasing population is a starving challenge for Zimbabwe, while soil degradation is negatively correlated with food security due to shrinking cultivated lands among the communal areas.

Soil erosion is a gradual process of washing away of soil or movement and transport of the upper layer of soil by different agents like water, wind, and mass movement leading to deterioration in the long term. The soil erosion is the major and visible form of soil degradation (Rodrigo Comino et al. 2017). There is high rate of accelerated erosion in the communal areas of Zimbabwe due to combination of relatively high population densities, lack of investment, and marginal agricultural terrain. This has resulted in serious problems of poverty and environmental degradation within smallholder farming systems. Soil erosion is a slow and discontinuous phenomenon that consists of the mobilization of detachments from the surface and that, in the long term, generates changes in the aspect of the land (Parwada and Van Tol 2018). The soil properties and erosive agents have a major influence on the rate and occurrence of soil erosion (Fig. 3). Therefore, soil erosion is inferred as a process of detachment, transportation and deposition of eroded soil particles. Thus, the natural sequence of the sediment cycle is as follows:

Detachment is the dislodging of the soil particle from the soil mass by erosive agents e.g. raindrop impact. This is prevalent in the communal areas of Zimbabwe as the soils are exposed to the raindrop impacts due to limited soil cover. In most cases, rainfall in these areas is usually received as heavy downpours with very high intensities and short durations which can easily detach the poorly aggregated soil. Wind also contribute significantly to the detachment and transportation of the soil in the communal areas especially late winter (August-September) season. During this period, dust storms are traditionally a common feature in the communal areas in Zimbabwe. It is evident that the erosion by water and wind are the most common forms of erosion in the communal areas of Zimbabwe. These two forms of erosion accounts for more than 70% of the soil degradation experienced among the communal farms (Parwada and Van Tol 2018; Nyamangara et al. 2020).

The energy of the erosive agent determines the amount and size of the sediments to be transported. In the highly erodible soils like those in the communal areas of Zimbabwe, permissible velocities should be decreased 25%. Soil cover reduce the



Fig. 3 Stages in soil erosion

energy of the erosive agents to transport and movement of detached soil particles from their original location. However, due to limited soil cover (<10%) in the communal areas, the water and wind can transport the detached soil particles for long distances.

At the detachment stage, soil erosion is often taken lightly and its effects are rarely perceived as severe. However, most communal areas in Zimbabwe are slowly transformed into gullies and if unchecked, this will destroy farming land, displace people, among other challenges (Parwada et al. 2022). Soil security has been greatly compromised by human activities among the communal area, particularly due poor cropping systems, stream bank cultivation, unplanned grazing systems and lack of soil erosion control mechanisms (Boardman 2006). Research has showed that intensive and short period rains as a result of climate change are also fuelling the formation of gullies in the communal areas of Zimbabwe (Parwada and Van Tol 2018).

Gully erosion persists >30 cm into the soil and is the worst type of erosion because soil conservation cannot take place through normal cultivation practices. This occur when runoff begins to flow strong and concentrates in one location and water flow can be strong enough to detach and move complete soil particles along with it (Fig. 4). This type of erosion is very extensive and visible and has drastic effects on soil productivity and restrict land use. The gullies can be ≥ 2 m deep but may be 10–15 m deep. The gullies are becoming a widespread feature in many communal areas of Zimbabwe and can be severe that some farmers e.g. Dete-Mabale, Matabeleland North (Fig. 4) are abandoning their fields (Parwada et al. 2022; FAO 2019).

The communal land is semi-permanent or permanently bare because the farmers harvest crop residues for construction and animal feed, burn crop residues during land preparation and cut down trees on their farms (Parwada et al. 2022). The bareness increases the speed of the erosion process or its cause. The main agents of soil erosion due to natural factors are water currents and wind storms, yet the situation may be aggravated by human activities as well. Zimbabwe communal areas have typically high proportion (52.5%) of bare soil (Zingore et al. 2005). Therefore,



Fig. 4 Gully development in the communal areas of Zimbabwe under two different land management (a) on grazing areas and (b) cropping area (photos taken in Dete-Mabale, Matabeleland North, 2021/22 summer seasons)

combining high rainfall erosivity (R-factor) with bare soil coverage lead to severe soil degradation and detrimental impacts on the resource soil. There is high erosivity in summer (October-April) season due to limited soil and groundcover hence high rate of water erosion. In winter (May-August), wind erosion is also high because the farmers remove the soil cover by harvesting the little crop residues (Parwada et al. 2022).

The erodibility of a soil as a material with a greater or lesser degree of coherence is defined by its resistance to two energy sources: the impact of raindrops on the soil surface, and the shearing action of runoff between clods in grooves or rills (Boardman 2006). Soil erodibility depends on the soil texture, the amount of organic matter, and the equivalent humidity of the soil (Parwada and Van Tol 2018). It is agreed that an increase of 1% in the amount of organic matter reduces soil erodibility by at least 5% and an increase of granules particles (>2 mm in diameter) by 10% in the surface horizon will reduce its erodibility by over 15%. When the percentage of the granular particles exceeds 40%, there is a decrease in the reduction in soil erodibility (Le Roux et al. 2007). This suggests that sand soils have lower erodibility factor (K-factor) compared to fine texture soils like clay.

3.1 Anthropic Erosion

Many studies agree that human activities such as land mismanagement, overgrazing, deforestation, transportation of people and goods, and so on are accelerating the rate of erosion world-over (Wang et al. 2022; FAO 2019). The accelerated soil erosion has resulted in heavily eroded artificial soil horizons e.g. the saprolitic soils are very common in most communal areas of Zimbabwe. Inappropriate land management and agricultural practices have increased rates of soil loss by 10–50 times compared to undisturbed forests (Boardman 2006). The anthropogenic factors have modified the process and forms of soil erosion directly and indirectly for example, a direct impact in the communal areas comes mostly from illegal small-scale mining and quarrying. The indirect effects are due to unsustainable management, disturbing the topsoil and increasing erodibility of fields and forest stands e.g. poor soil tillage practices and deforestation.

3.2 Droughts

Droughts are recurring natural hazards in Zimbabwe and have resulted in deterioration of soil health. The extreme process of soil degradation is known as **desertification** where a fertile land becomes a desert barren of life. The drought can affect soil chemical, physical, and biological activities that are essential for plant and soil health. Changes in soil temperature during drought conditions can influence soil organic matter (SOM) decomposition and increase the release of carbon dioxide.

During this process additional mineral N, mostly in the form of nitrate, will be released in the soil system. Extended periods of drought can [contribute](#) to soil erosion, but does not directly cause it. Drought reduce vegetation productivity, which normally would add to SOM that binds soil together against high winds or heavy rains. Drought can also reduce mineral N uptake by plants and reduced NO_3^- leaching and NH_4^+ oxidation, resulting in increased mineral N concentration (NH_4^+ and NO_3^-) for all ecosystems. The [effects of](#) drought on soil N pools can also be modified by two processes that are N mineralization and nitrification. Research showed that 90% of soil loss from runoff plots comes from only 10% of runoff events, and was almost entirely confined to periods when groundcover was below 50% (Parwada et al. [2022](#); Zuazo and Pleguezuelo [2008](#)). Therefore, drought and/or overgrazing influence the levels of soil erosion in the communal areas.

Another form of soil degradation among the smallholder farmers in Zimbabwe is soil [salinization](#). This form soil degradation is gradually becoming a cause of concern in the irrigated soils, where the excessive salts are affecting crop productivity by reducing their ability to uptake water. Salinization reduces [soil fertility](#) hence increases [desertification](#) of agricultural land (Wang et al. [2022](#)). Noting the high rates salinization worldwide, it has been projected that by 2050, about 50% of the world soil will be saline and difficult to mitigate (Boardman [2006](#); Pimentel and Burgess [2013](#)). Salinization also reduce soil productivity when salts levels built up or when [saline water](#) is used for irrigation and become harmful to crops. Therefore, if not controlled, the soil salinity can be serious threat to food security among the communal area of Zimbabwe.

4 Possible Strategies to Reclaim Degraded Soils in the Communal Areas of Zimbabwe

Food security to meet the requirements of the geometrically increasing population is a major challenge for every country world-over, but soil degradation is negatively correlated with food security due to shrinking cultivated lands (Corwin et al. [2007](#)). The human population census projected the world population to increase from 7.6 billion in 2018 to 8.3 billion and 9.2 billion in 2030 and 2050, respectively (FAO [2019](#)). To feed this population, we need to rehabilitate degraded soil and stop further degradation of productive soils. There are various strategies for the rehabilitation of affected soils according to the conditions prevailing there. It includes vegetation management and soil structure improvement for the control of erosion (Stocking and Murnaghan [2000](#)). Salt-affected soils need some chemical amendments and good quality irrigation water with comprehensive drainage system (Lai and Singh [1998](#)). For maintenance of soil fertility, it requires proper fertilizer and crop management (Pimentel and Burgess [2013](#)), while effects of heavy metals can be alleviated by in situ immobilization using some immobilizing agents and phytoremediation (Zuazo and Pleguezuelo [2008](#)).

Sustainable agricultural systems strive to restore and enhance inherent soil qualities and productivity through improved conservation and management practices, while reducing use of commercial inputs. Interest in organic agriculture has also grown dramatically. The production of organic food and fibre is largely dependent on building fertile, productive soils without the use of synthetic inputs. The public interest in agricultural production and products free of fertilizers and pesticides, expressed through the marketplace, both for human health and ecosystem health, has caused organic and sustainable production systems to flourish. Conservation practices, including the use of cover crops, will be a critical and societies that do not implement conservation practices across the tropics or even temperate or sub-tropical regions will be negatively impacted (FAO 2019). Policies for soil and water conservation and climate change adaptation will be essential if societies are to have an opportunity to adapt to a changing climate while maintaining. No-till practices have also been demonstrated to reduce soil erosion via wind by reducing the amount of soil macroaggregate turnover. Soils contain organic matter-mineral microaggregates that in favourable circumstances bind together to form macroaggregates (Rodrigo Comino et al. 2017). Recently, the government of Zimbabwe has introduced a soil conservation farming system called *Pfumvudza* that mainly aims at minimising soil disturbance and increase in soil organic matter in the smallholder farming sector. The *Pfumvudza* has the potential of reducing soil erodibility in the communal areas of Zimbabwe as it centres on increasing the soil organic matter (SOM) content.

Use of cover crops across the tropics to protect the soil surface and reduce erosion, improve soil health, and contribute to carbon sequestration, which will improve soil biological functions and cycle essential nutrients to increase yields. Cover crops can be used to increase yields among the communal areas of Zimbabwe. Cover crops can also contribute large quantities of nitrogen fertilizer equivalent, especially when leguminous cover crops are used to fix atmospheric nitrogen and cycle nitrogen to the next crop, on occasion up to 300 kg N ha⁻¹. A large number of other macro- and micro-nutrients are also cycled to the next crop, improving the nutritional value and protein content of the subsequent crop, which could potentially have significant positive impacts on human and animal nutrition. Mulching with straw usually prevents the soil surface from sealing and crusting. After rain, fields using these practices usually result in high soil water contents near the soil surface for a longer period of time and greater water infiltration into deeper soil layers. Therefore, mulching can reduce potential water erosion by minimizing runoff. For example, Zuazo and Pleguezuelo (2008) showed that after heavy rain a field of peas mulched with wheat straw increased water infiltration significantly and runoff decreased accordingly. Total sediments decreased by an average of 69% in the pea crop mulched with wheat straw compared with that in a pea field that was not covered with straw.

The farmers are highly encouraged to apply manure and gypsum in their fields because this improve soil structure and reclaiming sodic soils. Organic farming heavily rely on the use of manure and compost where farm diversity should be promoted by integrating livestock with cropping system. Parwada et al. (2020) reported

that applications of farm by products and organic manures enhanced the quality of sodic vertisols, increased soil organic carbon (SOC) contents and yield of crop. The SOC content was significantly increased by growing grass e.g. Karna grass (*Diplachne fusca*) and of application of gypsum within 3 years. In Zimbabwe, acid soils developed in high-rainfall area (e.g. natural region I > 800 mm year⁻¹) and have very low internal buffering capacity and low surface charge characteristics. These intrinsic soil attributes have significant impact on crop productivity. However, if the acid soils are managed properly, it could be productive and enrich the soil with carbon.

Relay Cropping (RC) has potential to control soil erosion and thus to serve as a proxy for conservation measure on too steep slopes, which are not adapted for the conventional cropping system. The 'soil conservation' activity in the RC can be achieved in two ways: by sowing into the standing crop that requires planting of the second crop under no tillage (at least between rows) and by eliminating the fallow period (Pimentel and Burgess 2013). Relay cropping permits sowing the first crop (hereafter referred to as primary crop) with conventional sowing dates while allowing planting of the second crop (hereafter referred to as relay crop) at an optimal planting date and at a time when soil moisture is more readily available. This means that RC may represent a very versatile system in terms of crop management practices provided that the latter are well-planned in advance.

Crop residue management (CRM) through [conservation agriculture](#) can improve soil productivity and crop production by maintaining [SOM](#) levels. Two significant advantages of surface-residue management are increased OM near the soil surface and enhanced nutrient cycling and retention (Pimentel and Burgess 2013). Greater microbial biomass and activity near the soil surface acts as a reservoir for nutrients needed in crop production and increases structural stability for increased [infiltration](#). In addition to the altered nutrient distribution within the soil profile, changes also occur in the chemical and physical properties of the soil. Improved soil C sequestration through enhanced CRM is a cost-effective option for minimizing agriculture's impact on the environment. Crop residue of common agricultural crops are important resources, not only as sources of nutrients for succeeding crops and hence agricultural productivity, but also for improved soil, water and air quality. The development of effective CRM systems depends on a thorough understanding of factors that control residue decomposition and their careful application within a specific crop production system. Improved residue management and [reduced tillage](#) practices should be encouraged because of their beneficial role in reducing [soil degradation](#) and increasing soil productivity. These practices, in addition to organic amendments, are important in mitigating unexpected drought conditions in the long-term. These practices, along with minimum or no-tillage, can reduce the prolonged impact of drought events by increasing soil resiliency.

5 Alternate Land Use and Afforestation

Land use management is very key to the conservation and degradation of soil (Le Roux et al. 2008; Gafur et al. 2000). The converting non-forest land to forest promotes diversity of flora and fauna, except in plantations of monocultures and especially exotic species. Afforestation and reforestation can achieve restoration of degraded lands and has numerous co-benefits on the environment, e.g. mitigation of erosion and salinization. In dry areas, increasing of forested areas can be an important desertification-reduction activity. Afforestation and reforestation are essentially important in raising the annual carbon sequestration rates in aboveground and below-ground biomass of 0.4–1.2 Mgc ha⁻¹ year⁻¹ in boreal regions, 1.5–4.5 Mgc ha⁻¹ year⁻¹ in temperate regions, and 4.0–8.0 Mgc ha⁻¹ year⁻¹ in tropical regions (Wang et al. 2022; Zuazo and Pleguezuelo 2008). Hence the maximum average potential of C sequestration rate would be 1.1–6 GtC year⁻¹ in both above and below-grounds if re-vegetation is done (Wang et al. 2022).

It was observed that altering land-use systems like promoting agroforestry and agro-horticulture culture can promote SOC restoration than the commonly practiced sole cropping system (Parwada et al. 2022). Corwin et al. (2007) showed that organic C content was double in agroforestry systems in comparison to the sole cropping. Both SOC and microbial biomass carbon (MBC) in agroforestry systems was significantly higher than in either of the sole cropping system (Parwada et al. 2022; Zuazo and Pleguezuelo 2008). Pimentel and Burgess (2013) also indicated that vegetable growing plots had similar SOC contents as field crop growing plots. This suggest that the communal farmers in Zimbabwe should aim at diversifying their cropping systems in order to build up the low SOC which will in turn modifies the physico-chemical properties.

6 Reclamation of Sodium-Affected Soils

Soils with high concentration of exchangeable sodium are common in some communal areas of Zimbabwe where the geological parent material is high in sodium containing minerals. Such soils are characterised by deflocculated clays making them mechanically unstable hence high rates of soil erosion. However, efforts to reclaim and stabilise the sodium-affected soils are affected by an inadequate knowledge of the basic physical and chemical factors of the soils. Reclamation of sodic soils is needed to lower the rates of runoff and erosion in sodic soils. In the reclamation the exchangeable Na is replaced by Ca. The farmers can apply Ca containing materials to the sodic soils e.g. [gypsum](#), calcium chloride and the soil itself as it is involved in the dissolution of Ca-containing minerals (Corwin et al. 2007). Chemical amendments may also be effective in restoring water penetration after reduction caused by either excessive adsorbed sodium in the applied water, however, are not

be effective if low permeability is due to [soil texture](#), compaction, or water-restricting layers (Wang et al. [2022](#); FAO [2019](#)).

7 Conclusions and Recommendations

Most soils in the communal areas of Zimbabwe are severely degraded such that they are no longer productive. Crop yield is continuously declining thereby risking the food security status of the people. The degraded lands are reserved for grazing and firewood harvesting as their agricultural production potential is negligible. The communal farmers should find alternative land use practices and need to transform from the traditional sole cropping practices and unplanned grazing systems which promote soil degradation, to more diversified cropping and livestock production systems. Soil reclamation should aim at reducing the rainfall erosivity and soil erodibility in their farms. Reduction in rainfall erosivity can be achieved by promoting permanent soil cover e.g. use of cover crops and agroforestry whilst any land management practice like conservation agriculture and green manuring which increase the SOC content will reduce the soil erodibility. The soil reclamation strategies highlighted in this chapter should be a general guide, and local conditions need to be assessed before designing surface water management structures. To avoid this generalization, there is need for research on testing the appropriateness of the strategies in different farming areas in Zimbabwe.

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Part III

Future Strategies

Exploring Biotechnological Strategies in the Monitoring of Soil Quality



Linda U. Obi, Frances N. Olisaka, Christabel Ene, and Uchenna Aniakor

1 Introduction

Soil quality refers to soils' ability to promote biological productivity, preserve environmental quality, and advance fauna and flora health within the constraint of an ecosystem. The quality of soil is not limited to its agroecosystem productivity in terms of supporting plant growth; it also encompasses the natural ecosystem of sustaining biodiversity and environmental quality such as water purification, carbon sequestration, etc. (Bünemann et al. 2018). The chemical, physical and biological features of soil account for its general quality. Environmental disturbances such as drought, salinity, pollution, climate changes as well as human activities which include agriculture adversely impact soil quality which subsequently results to land degradation, loss of soil fertility, and biodiversity. Low/poor soil quality can be attributed to different physical, chemical, and biological degradation due to climate change, pollution, erosion, drought, salinity, soil compaction, decline in soil biodiversity, and different anthropogenic activities. Climate change and water erosion

L. U. Obi (✉)

Department of Biological Sciences, Faculty of Natural Sciences and Environmental Studies,
Godfrey Okoye University, Enugu, Enugu State, Nigeria

Microbiology and Environmental Biotechnology Research Group, Agricultural Research
Council—Natural Resources and Engineering, Pretoria, South Africa

F. N. Olisaka

Department of Biological Sciences, Faculty of Natural Sciences and Environmental Studies,
Godfrey Okoye University, Enugu, Enugu State, Nigeria

Department of Biological Sciences, Faculty of Science, Benson Idahosa University,
Benin City, Edo State, Nigeria

C. Ene · U. Aniakor

Department of Biological Sciences, Faculty of Natural Sciences and Environmental Studies,
Godfrey Okoye University, Enugu, Enugu State, Nigeria

have been predicted to cause the reduction of soil organic carbon concentration through water erosion (Borrelli et al. 2020; Rust et al. 2022). Abiotic factors, such as drought and salinity, render approximately one billion hectares of global arid and semi-arid lands unproductive and infertile (Sahab et al. 2021). The accumulation of both organic and inorganic pollutants resulting from anthropogenic activities such as deforestation and environmental pollution also has an adverse effect on soil health and productivity (Zong and Lu 2019). This could also impact the microbial population and diversity of the soil and possibly lead to the deterioration of soil/land. Land deterioration is a global environmental challenge owing to its detrimental impact on about three-fourths of the global terrestrial ecosystem. Excessive anthropogenic activities have detrimental consequences on the ecosystem, manifesting in decreased soil productivity, loss of biodiversity, and potential disruptions in food production. Furthermore, these activities contribute to climate change through the release of carbon emissions into the environment. These emissions act as a heat-trapping mechanism, causing alterations in the Earth's climate system, which result in global warming and the occurrence of extreme weather events (IPBES 2019; Santini et al. 2022). Possible solutions to avert the detrimental effects of this ecosystem's degradation focus on sustainable management of lands and productivity. In accordance with the Sustainable Development Goals (SDGs) set forth by the United Nations General Assembly in the 2030 Agenda for sustainable development, protection and sustainable management of terrestrial ecosystems as well as combating climate change and its impact by reducing our carbon footprints respectively corroborates SDG 15 and 13.

Possible mitigation strategies for the effects of poor soil quality include the evaluation of soil functions and using various monitoring indicators. To evaluate soil quality, several soil monitoring indicators (Fig. 1) have been put to practical applications and have been categorized into physical chemical, and biological indicators. Physical indicators deal with water retention capacity as well such as nutrient availability in the soil ecosystem. Measuring physical indicators of soil quality, including factors like soil porosity, texture and structure, can be quickly and easily done using simple tools and techniques. By correlating these measurements with other methods of monitoring soil health, we can gain a more comprehensive understanding of soil health and identify specific management practices to improve soil quality. However, this technique has some limitations, including a lack of precise information, which may make it difficult to monitor alterations in soil quality over time and can lead to variability in measurements and unreliable data. The chemical indicators which comprise soil pH, soil organic matter, available nitrogen, phosphorus, and potassium describe the balance between soil moisture, nutrients, etc. Low soil pH reduces the availability of some nutrients such as phosphorus and calcium while soil organic matter improves water-holding capacity and nutrient retention in the soil (Feng et al. 2019; Čechmánková et al. 2021). Some biological entities which participate in the process of nutrient cycling and the breakdown of organic matter are referred to as biological indicators of soil quality (Doran et al. 1996). Additionally, assessing the activities and diversity of microbial communities in contaminated environments can be used to monitor the impact of hazardous chemicals on the



Fig. 1 Different indicators of soil quality

environment through the process of bioavailability. Bioavailability refers to the degree to which a chemical substance is accessible and can be utilized by living organisms in a particular environment.

Microbes, such as bacteria and fungi, possess unique biochemical capabilities that enable them to interact with and transform various chemical compounds in their surroundings. Microbes actively participate in the degradation, immobilization, or transformation of environmental contaminants. The presence of specific microbial species or metabolic pathways can indicate the ability of these organisms to degrade or transform particular chemicals (Pileggi et al. 2020). Changes in microbial diversity and population as well as microbial activities aid in the identification of possible signs of soil degradation. Swift response to environmental stress/changes and adaptability are some of the characteristics of microorganisms as biological indicators of environmental alterations. Over the past decade, advancements in microbial biotechnology have enabled the full genomic identification and functional analysis

of soil microorganisms, which play crucial roles in various natural processes (Vieira et al. 2021). Microbial biotechnological advancements such as the ‘omics’ technology which includes metagenomics, metatranscriptomics, metabolomics, proteomics, etc. offer powerful tools for understanding the complex interactions between microbial communities and pollutants in contaminated environments. They provide valuable information for optimizing and enhancing phytoremediation and micro-remediation strategies, leading to more efficient and sustainable approaches for environmental remediation (George et al. 2019; Withers et al. 2020). This creates an advantage over conventional indicators for the monitoring of soil quality (Nielsen et al. 2002). A study by Bhowmik et al. (2019) deduced the potential of soil enzymes and microbial communities to indicate the degradation of soil quality in a watershed as well as their relation to the physicochemical properties of soil. The inclusion of molecular and biotechnological strategies as possible means of monitoring soil quality is essential considering recent developments in that field which include advancements in DNA sequencing technologies, the development of novel bioindicators as well as the inclusion of nano biosensors. The importance of these techniques relies on the potential of the techniques to promote productivity and sustainability. This chapter focuses on the causes of low soil quality, potential mitigation strategies, as well as an analysis of different biotechnological approaches and their effect on monitoring soil health and quality.

2 Characteristics of Soil Quality

Soil quality refers to a particular type of soil’s ability to promote productivity of crops and livestock, preserve or improve the quantity of the environment, including air and water, as well as promote the well-being of humans (Stivers 2017). Soil quality is the term used when referring to soils that have beneficial physical and biological attributes and are fertile. Environmental quality has three elements; these elements are water quality, air quality, and soil quality. The quality of the environment is defined by the extent of pollution in the air and water, this directly impacts natural ecosystems and human and animal consumption (Bünemann et al. 2018). In the definition of soil quality rather than being limited to the extent of soil pollution, the basic definition of soil quality is that it is the ability of soil to perform its tasks within an ecological system and the use of land to preserve environmental quality, maintain biological productivity, and promote animal and plant health (Bünemann et al. 2018). Soil quality is an external attribute of soils that changes with the desired use of that soil by humans. This could be directly associated with agricultural productivity and the ability to support wildlife, protect watersheds, or provide leisure opportunities (Tahat et al. 2020).

The cornerstone of sustainable farming practices is good soil quality. Fertile soil provides the vital nutrients that plants need to grow. Air and water can penetrate the roots of plants owing to significant physical aspects of aggregation and structure of soil. Soil quality links agricultural and soil research to policymaking, stakeholder

expectations, and the management of sustainable supply chains. The soil's continuous ability to function as an essential biological ecosystem that nourishes humans, animals, and plants is soil quality. In the past, soil assessments were mainly concentrated on crop output; currently, soil quality also examines the impact of soil on human health, water quality, and climate change (Lehmann et al. 2020). Despite rising recognition of the significance of soil biodiversity, assessing soil quality continues to be dominated by chemical markers due to a lack of practical information about efficient techniques (Lehmann et al. 2020).

2.1 Different Indicators of Soil Quality

Since soil quality is a wide, integrative, and context-dependent notion, it cannot be directly measured. Instead, we examine some proxy data that, when combined, reveal information about how the soil is behaving from one or more soil-use perspectives. Indicators of soil quality are what these measurements are named. An efficient indicator set is a collection of inexpensive, easily measurable indicators that reliably predicts important soil processes. The features of soil solids, soil solutions, soil atmospheres, plants, and other soil biota are examples of soil quality indicators. They may also incorporate economic studies of land use or ecosystem services. Regardless of the approach chosen, the process of evaluating soil quality follows the same fundamental steps: identification of soil usage issues, followed by indicator selection and interpretation. To put it more precisely, one must first establish the land-use objectives before proposing, measuring, and evaluating indicators across a representative collection of lands and management approaches. These activities take place at several levels and are influenced by both natural soil properties (such as texture, OM content, pH, CEC, porosity, etc.) and external environmental (such as climate, topographical, hydrological, and biological) as well as anthropogenic (soil-use and management) factors. Some features associated with soil quality include:

2.1.1 Soil PH

The capacity of soil to provide the nourishment crop varieties require to thrive is known as soil fertility. The primary nutrients that plants take up from the soil are the following: phosphorus, potassium, calcium, nitrogen, and magnesium. Additionally, we generally need to supplement the nutrients in the soil with sustainable compost, manure, or fertilizer for optimal development of crops. The pH level of the soil is yet another vital component of fertility in the soil. The pH of the soil has an important effect on soil biogeochemical activities in the natural environment. The “master soil variable” is the soil's pH, and it influences a variety of soil chemical, biological, and physical properties as well as processes that have an impact on plant growth and biomass production (Dora 2019). PH regulates biological processes and soil

biology and this results in pH and fertility of the soil having a bidirectional relationship.

Several nutrients needed by plants become significantly easier to obtain and this availability depends on the pH of the soil. Neutral soils include those which range between a pH that is slightly acidic at around 6.5 and a slightly alkaline pH level of 7.5 and this is considered to be near to the “ideal” soil pH. Within this pH range of 6.5 to 7.5, the majority of plant nutrients are optimally available to plants, and this pH range is typically very beneficial to plant development of root systems. Three main plant nutrients which include potassium (K), nitrogen (N), and sulfur (S) seems to be less significantly affected by soil pH than many other nutrients but they are affected nevertheless. However, from the three main nutrients, phosphorus (P) is the first to be affected. For instance, at alkaline pH levels higher than pH 7.5 calcium (Ca) and magnesium (Mg) typically undergo fast reactions with phosphate ions that result in less soluble compounds, also at acidic pH levels, phosphate ions undergoes reactions with iron (Fe) and aluminum (Al) to generate less soluble molecules. When soil pH surpasses 7.5, the majorities of other nutrients (especially micronutrients) are not as available and are most easily accessible at a slightly acidic pH, which ranges from 6.5 to 6.8. Molybdenum (Mo) seems to be easier to obtain at slightly alkaline pH values whereas it is less accessible at acidic pH levels (Dora 2019).

Soil pH is an important indicator of soil quality. In light of this, reliable pH sensing continues to be vital in soil quality assessment and monitoring. The application of nanoparticles (NPs) for determining pH has gained increasing attention recently, particularly for imaging and intracellular pH sensing. As a result of this, numerous nanoparticle based fluorescent pH sensors have been created for this purpose. They can be categorized into three main categories: fluorescent nanoparticles with either indirect or direct pH responses; non-fluorescent NPs utilized solely as scaffolds and recipients for pH-sensitive fluorescent dyes; and non-fluorescent nanoparticles whose pH-responsive structural modification is transformed to the fluorescence indicator associated with their attached dyes.

2.1.2 Organic Matter

Remains of plants and animals, alive and dead soil microbes, and compounds created during decomposition make up organic matter. Organic matter makes up a very small fraction of the majority of agricultural soils, but it majorly influences soil quality (Stivers 2017). Organic matter in the soil has the tendency to enhance soil biological activity, soil structure, and fertility. Cover crops, manure, compost, and crop rotation are some of the means used to add organic matter to soils. Soil organic matter can alter how bioavailable pollutants are to the soil by immobilizing or mobilizing pollutants by creating various complexes that could be either insoluble or soluble (Shrestha et al. 2019).

The impact of soil organic matter (SOM) on various properties of soil which can be either chemical, physical and biological influences soil function and directly

contributes to the growth of both plants and microorganisms (Vinh-Freitas et al. 2017). The primary source of exocellular hydrolytic enzymes involved in these cycles; nitrogen (urease) cycle, carbon (beta-glucosidase) cycle, phosphorus (phosphatase) cycle, and sulfur (arylsulphatase) cycle in soils is soil microorganisms. Exocellular hydrolytic enzymes function on the breakdown of organic materials to release micronutrients into the soil solution that are then available to microbes and for plant growth. In addition to enzymes, there are several biochemical measures that serve as indications of microbial activity, including metabolic quotient, fluorescein diacetate activity, and soil microbial respiration (qCO_2) (Vinh-Freitas et al. 2017).

2.1.3 Soil Texture

The ratio of sand, clay, and silt in soil is used to determine its textural class. To generate soil sand, clay, and silt are normally combined together. Medium-sized particles make up the silt, sand particles are extremely huge and clay particles are smaller than sand particles. Clay and silt particles hold more fluid and plant nutrients along their surfaces than sand particles do. The fundamental characteristic of soil texture is not significantly impacted by various management strategies. The four main textural classifications of soils are loams, sands, silts, and clays. Soil texture impacts soil moisture content and drainage capacity. This is due to the fact that texture determines the soil pores, which are openings or spaces between mineral particles in clay soil. The balanced supply of both air and water in loamy soil is a result of its composition of both sand and clay and also because of its macro and micro holes.

The ability of soil to give nutrients to plants is affected by soil texture. Coarse textured soils, for example, are poor in nutrients, this is because leaching is significant in these soils and nutrients are being transported out of the soil. Burke and Hook discovered a high link between soil C and N pools and N turnover dynamics and both landscape position and soil texture (Amooh and Bonsu 2015). Since it directly impacts the water content of the soil and its temperature, the texture of soil has an impact on microbial activity (Vinh-Freitas et al. 2017). In terms of soil porosity and its aggregation, the textural class is equally vital. Moreover, gas exchange (microbial respiration and respiration of roots) between the atmosphere and soil is significantly influenced by soil texture. Within the same soil class, heavily-textured soils exhibit higher levels of carbon stock and microbial activity than light-textured soils. The texture of soil is crucial in determining how vulnerable soil is to various land uses especially those used for agricultural purposes (Vinh-Freitas et al. 2017). The understanding of the function of soil and its ecological processes can be enhanced by research on microbial, biochemical, and soil texture indicators.

2.1.4 Compaction

When pore spaces contract and soil particles are forced closer together, soil compaction results. When large tractors, trucks, and other machinery are driven over the soil, especially when the earth is moist, this generally happens. At the soil's surface as well as in the layer of soil immediately below the depth of tillage, soils can get compacted (subsoil compaction). Compacted soil makes it harder for plants to grow because the soil aggregates are compressed, leaving little pore space for water and air, both of which are necessary for root growth. Soil compaction can also have an effect on bigger burrowing species since burrowing in compacted soils consumes more energy than other activities like foraging and breeding (Tibbett et al. 2020). Furthermore, when there is an increase in bulk density, it often correlates with a decrease in the moisture content of soil and its organic matter. These changes can have significant implications for the community assemblages present in the soil, including burrowing species and plants (Tibbett et al. 2020).

The extent of the soil's modification during compaction can be determined by the soil's physical, physicochemical, and biological parameters such as bulk density, shear strength, penetration resistance, pH, redox potential, CO₂ efflux, and microbial activity. In-situ or laboratory measurements of these qualities using soil samples are also feasible; however, this method might not always be the most effective approach to assess soil modification, particularly over vast areas of space.

A potential, albeit mostly unexplored, resource for geographically and temporally uniform examination of compaction in soil and rutting in forest systems has been provided by the latest developments in remote sensing. Across a restricted spatial extent, Cambi et al. (2018) reported that the use of high-resolution photogrammetry might potentially be used to calculate soil compaction proxies that are comparable to in-situ measurements. Similarly to this, Talbot et al. (2018) assessed the severity of soil rutting following forest cutting using unmanned aerial vehicles (UAVs) fitted with digital cameras and producing 3D images. However, a UAV-based approach like this can only be used in relatively limited spatial extents and over recently clear-cut or harvested areas. Light detection and ranging technology (LiDAR)-based terrestrial laser scanning (TLS) has been put forward as an alternative method to monitor soil compaction and rutting from beneath the protective covering (Koreň et al. 2015).

2.1.5 Soil Biological Activity

Living things such as bacteria, fungi, insects, earthworms, and others are abundant in healthy soil. These living organisms enhance soil quality by carrying out a variety of tasks as they go through their life cycles. Organic matter which include crop waste and manure from livestock farming, is broken down by soil organisms. They facilitate the bonding of soil particles into durable aggregates. They also produce humus, an organic material that doesn't further disintegrate and aids in keeping soils moist and nutrient-rich. More biologically active soils typically include fewer

organisms that cause plant diseases. By digging tunnels through soils, earthworms create access points for air and water to penetrate the soil.

Soil biodiversity decrease is commonly defined as a fall in the number and variety of life living in soils (Tibbett et al. 2020). Wherever soil biodiversity decrease happens, it can have a substantial impact on the soil's functionality, its ability adapt to perturbations, and recover. Several soil hazards, such as human intense exploitation, soil organic matter decrease, and land-use change, have been shown to have a negative impact on soil biodiversity (Gardi et al. 2013).

The conventional techniques for detecting microbial communities are time-consuming and need expensive equipment. Stable isotope probing, DNA fingerprinting, 16S rRNA gene sequencing, and nanotechnology, are methods available for identification of soil microbial populations.

2.2 Possible Causes of Poor Soil Quality

Loss of soil productivity and quality is referred to as soil degradation. It might happen naturally as a result of the topography, climate, and soil's innate traits. Deforestation, excessive grazing, and improper agricultural land management are examples of human interventions that can be controlled or avoided that cause soil degradation. Human-induced deterioration occurs more quickly than natural degradation does. SOM, or soil organic matter, is often used as a measure of deterioration in soil. More organic matter in the soil improves its structure, increases water infiltration, and makes the soil more resistant to desertification, compaction, and erosion. Monitoring and evaluating soil degradation processes' using the right techniques is crucial to stop soil degradation processes from worsening soil physical, chemical, and biological properties (expert-based, remote sensing, or modeling). Below are some causes of soil degradation:

2.2.1 Erosion

Soil erosion caused by water, is the most frequent source of soil degradation worldwide which leads to loss of soil, increased pollution, and sedimentation in rivers. Putting into consideration the mechanisms of degradation of land, it has been estimated that soil and water erosion affects eighty percent of Africa's soils. Particularly, in the Sahel belt south of the Sahara, crusting of soil can increase water runoff and sheet erosion. Also water erosion is thought to be responsible for up to thirty million tons of lost soil in Nigeria (Hossain et al. 2020). Wind erosion adds significantly to soil movement and high wind speed in semi-arid and dry zones, for instance, in Burkina Faso, it has been calculated that wind erosion contributed 329 t (ha⁻¹ year⁻¹) in soil loss, primarily from June to August prior to the advent of rain (Hossain et al. 2020).

The long-term repercussions of soil erosion on agriculture are visible. Soil erosion may diminish crop yield, and correcting it with locally available methods will be difficult. By decreasing the soil's organic matter, nitrogen, and phosphorus reserves in addition to its clay content, water-holding capacity, and soil aggregation, soil erosion lowers the productivity of crops. It is also reported that in instances involving severe soil erosion, pH, calcium, and potassium rise while iron; soil organic matter, phosphorus, nitrate-nitrogen, and zinc decrease (Chalise et al. 2019). Maintaining the condition of an outer layer of protection (trees, mulches, and crops), choosing the best land use, and building technological works (such as check dams) on the riverbed are the main methods for controlling soil erosion.

2.2.2 Organic and Inorganic Contaminants

In modern times, synthetic molecules of organic matter are present all around us. They are often found in our homes, our workplaces, in agriculture, and in public places. Organic pollutants are frequently identified far from their place of origin and can contaminate the soil, the water and the air through local contamination. Petroleum products, industrial solvents, pesticides, explosives, dioxins and furans, brominated flame retardants, and polychlorinated biphenyls (PCBs) are among the synthetic organic materials that are of concern as environmental contaminants. Various nutrients, toxic metals, and salts are examples of inorganic pollutants and these pollutants commonly occur as dissolved anions and cations. Several inorganic pollutants remain in the soil indefinitely, whereas other chemicals only degrade or change over a very brief period. Inorganic pollutants have a negative impact on the biological, physical, and fertility aspects of the soil, resulting in a decrease in productivity.

Organic and inorganic contaminants can have an adverse effect on the mechanical strength of soil, soil aggregation, and stability of soil by changing cation-exchanging capacity (CEC), soil pH, salinity, and dispersing and/or flocculating clays (Zong and Lu 2019; Salem et al. 2017). Very high soil NPK (Nitrogen, Phosphorus, and Potassium) levels improve plasticity index, bulk density, tensile strength, and coefficient of linear extensibility while drastically reducing water retention capacity, total porosity, and macro aggregate content (Zong and Lu 2019). Through volatilization and denitrification, soil contamination allows enormous amounts of nitrogen to release into the surrounding environment (Fungo et al. 2019). The interaction between pollutants in the soil and microorganisms and its interference with their regular metabolic processes reduces the production and fertility of the soil (Saxena et al. 2015; Behera and Prasad 2020).

Biological processes have proven to be the most effective way of removing synthetic organic and inorganic contaminants from polluted soils, and this method may be referred to as clean technology (Kumar 2020). Biotransformation, mycoremediation, phytoremediation, bioaugmentation, biomineralization, genoremediation, bioleaching, biostimulation, biosorption, bioadsorption, bioventing, are all examples of biological remediation methods for synthetic organic and inorganically contaminated soil.

2.2.3 Climate Change

Climate change can have both an indirect and direct impact on soil functions. A few examples of the direct effects of climate change on soil function and, consequently, soil quality include changes in nutrient cycling due to freeze-thaw (FT) cycles, changes in organic carbon transformations and changing soil moisture, as well as higher rates of soil erosion caused by a spike in high-intensity rainfall events. The soils' ability to successfully carry out its functions can be altered by the management of soils and climate change, which may negatively impact soil quality. Modifications in the soil's properties have an effect on how the soil performs particularly how effectively the soil transports biomass, retains water, and promotes plant growth (Ascough et al. 2019).

Functionality of soil is affected indirectly by the impacts of climate change which include those brought on by climate change mitigation techniques which include: rotation of crops, proper irrigation and tillage practices (Hamidov et al. 2018). Reduced crop yields (and subsequently debris inputs) might occur as a consequence of elevated temperatures, though this would typically be offset by the CO₂ fertilization effect, and in general, greater grass yields are anticipated. Considering the short term effect of climate change, both climate warming and increasing CO₂ levels in the atmosphere will promote tree growth (Jaihoon 2019). More studies could be done on the long-term effects of climate warming and CO₂ levels on tree growth. Through improved handling of N fertilizers, including the appropriate rate, type, and technique for application as well as soil management (avoiding soil compaction), nitrous oxide emissions can be decreased. By supplying a protective soil cover and an environment that encourages robust plant growth, sustainable agricultural strategies (minimal disturbance of the soil, cultivation of cover crops, and rotations of crops that include legumes) can restore soil organic matter (Goa and Zewude 2021).

Agricultural management can help to alleviate the consequences of climate change; one example of this is by increasing soil organic carbon sequestration (Haddaway et al. 2015). Hamidov et al. reviewed several scenario studies on climate change mitigation strategies that include agricultural adaptation options as a response to climate change. These strategies have been conducted in Europe and they include; crop rotation changes, the implementation of proper irrigation regimes in drought-prone areas, amended soil tillage practices, increased fertilization rates on cropland and the cultivation of melting permafrost soils (Hamidov et al. 2018).

2.2.4 Salinity

Soil salinization is a common cause of land degradation around the world (Rath and Rousk 2015). It has been observed to lower enzymatic activity, soil respiration, bacterial growth rate, and soil microbial biomass; all of these features affect the salinization of about 830 million ha of arable land globally and influence biogeochemical cycling (Zhang et al. 2019). Understanding the function and structure of

microbial communities in saline soil is an important goal in ecology since it will aid in elucidating the biological control mechanisms for nutrient cycles in saline soil. The microbial community in the soil is well known for driving the soil nutrient cycle in a variety of land habitats, may change as a result of soil salinization.

Due to human influence, changes in land use, and soil deterioration, there is less soil organic carbon than there was previously. Through increased carbon dioxide (CO₂) emission and lower plant intake, this drop has considerably contributed to the enrichment of atmospheric CO₂ (Raj et al. 2012). Saline soils are prevalent among degraded soils and according to Lal (2001), saline soils have a significant capacity for storing carbon (C) in above-ground biomass and in the soil organic carbon, also according to Chowdhury et al. (2011), salinity primarily impacts microorganisms by lowering their osmotic potential, which in turn reduces their activity and alters the makeup of the microbial community (Raj et al. 2012). These modifications affect the decomposition of soil organic material and in turn, affect carbon fixation in the soil. The two opposing processes that affect soil organic carbon content in saline soils are reduced plant inputs, which could reduce soil organic carbon, and reduce rates of decomposition, which might increase soil organic carbon content if the carbon supply remained constant (Raj et al. 2012).

Actinobacteria, *Planctomyces*, and *Proteobacteria* are a few bacterial groups that could support dissolved inorganic carbon fixation (Zhang et al. 2019). The promotion of dissolved inorganic carbon fixation would in term mitigate the effects of salinity by fixing the increased soil organic carbon content in saline soils.

2.2.5 Industrial Plant Activity

For any activity, the qualities of the soil are crucial. Numerous soil contaminants have different effects on the chemical properties of the soil. According to reports by Awotoye et al. (2011); Izah et al. (2016) and Okwute and Isu (2007), absorbing effluents from soil obtained from a palm mill contains processing mill rubble and moist soil (Seiyaboh and Izah 2019). Studies have also shown that the properties of the receiving soil may change as a result of cassava processing activities (Izah et al. 2017, 2018). The flora and fauna in this area may benefit or suffer due to variations in the soil's properties. For instance, according to Izah and Aigberua (2017), absorbing effluents from soil obtained from a cassava mill reduce the quantity and variety of bacteria that exists in the receiving soil (Izah et al. 2017). This suggests that the pollutant's chemical makeup may have an impact on the soil's flora. There have also been documented cases of cassava mill effluents reducing plant productivity in literature (Izah et al. 2018). Some of the pollutants in the soil may also provide the soil with necessary nutrients, increasing productivity.

2.3 Potential Effects of Poor Soil Quality on the Economy

2.3.1 Loss of Agricultural Land

The deterioration of chemical, natural or biological traits and attributes of agricultural land is referred to as agricultural pollution of the land. It causes a negative impact on every animal, person, or plant that lives on its surface, either directly or indirectly. Pollutants of agricultural soil consists of residues from agriculture practices which includes; associated weeds, plant remains and roots left over after burning the ground, crop stalks, remains from vegetable, leaves from trees, and fruit that is unripe that has fallen to the ground (Al-Yasiri 2019). Because soil contamination is a persistent issue, it differs from other types of pollution. By addressing the disease's causes before deciding on a course of therapy, it can be entirely removed and eliminated.

Agricultural land pollution negatively impacts economic growth and development by damaging people's livelihoods, enterprises, education, and occupations. Additional negative consequences of agricultural land pollution on economic expansion and the environment include biodiversity loss and reduced food and agricultural output levels. Many locals in the Nigerian region of the Niger Delta lose their jobs, such as canoe carving, fishing, and forestry, which together account for about 70% of all employment in the area. As a result, the majority of children in those households frequently drop out of school because their parents are unable to afford their wards' school fees (Ipingbemi 2009). It is indeed obvious that agricultural land pollution lowers household income levels thereby sustaining impoverishment. As a result, agricultural land pollution and poverty have a close relationship.

2.3.2 Loss of Biodiversity

The diversity of life in soil fuels ecosystems that sustain life above ground, and promotes healthy environments, and has been mostly overlooked in global agendas despite its vital function in sustaining the well-being of humans and natural systems. The majority of the Earth's biological biomass is contributed by organisms that exist in the soil, including fungi, bacteria, nematodes, moles, earthworms, and even plant roots (Bach et al. 2020). These organisms additionally constitute over twenty-five percent of the total documented species. Several ecosystem functions, including pathogen management, the cycling of nutrients, establishing the fundamental blocks of food webs, water absorption, and the maintenance of agroecosystems, are made possible by the complex interactions and activity of soil organisms. Soils and soil biodiversity are under threat by climate change, degradation of the land, pollution, excessive usage, growing urbanization, and abuse, and similar to the vast majority of the resources on which mankind depends (Bach et al. 2020).

There are many instances that demonstrate the significance of soil biota in sustaining global food production. In China, conventional rice-fish farming involves

the utilization of rice fields as fish habitats, where fish consume microorganisms that break down dead leaves of rice as food. The process of fish feeding breaks down the soil, enabling greater amounts of oxygen to penetrate. That, in turn, encourages the microbial breakdown of fish feces and plant matter, resulting in the release of nutrients that are needed by growing rice plants (Liu et al. 2013). Similar to the above, changing legumes with grain-based crops in industrial row-crop systems utilize the nitrogen-fixing bacteria associated with the legumes to create soil nitrogen that grain crops like maize subsequently utilize.

The repercussions of unsustainable resource usage at the local as well as global levels have become increasingly visible, raising questions about the connection between economic expansion and countless environmental quality initiatives (Dietz and Adger 2003). The declining level of biodiversity is also caused by of the complicated relationships between several triggers, including the equally complicated effective demand for wilderness, agricultural growth and conservation, recreational space, and conservation of genetic diversity for use in agricultural activities and production of pharmaceuticals. The advantageous effects of biodiversity are subsequently underestimated by society when weighing the manner in which they are allocated (Dietz and Adger 2003).

2.3.3 Increased Soil Erosion

Extreme soil erosion can have both economic and environmental consequences. Loss of farm household income due to reduced agricultural and farm animal output has an economic impact, while natural water and pollution of land have an environmental impact. Additionally, both on and off-site impacts of soil erosion on productivity may occur. Off-site implications include sediment obstruction in streams, contamination of water, and damage to physical infrastructure, while on-site impacts include agricultural degradation, loss of nutrients, and loss of fertile topsoil (Posthumus et al. 2015). When topsoil depth is lost, the situation becomes severe. Tillage-induced erosion, in addition to rain and wind erosion, is responsible for the loss of topsoil in cultivated fields that are on a steep slope. It has been shown by researchers that soils lost to erosion are 1.3 to 5 times richer in soil organic matter (SOM) than soils left behind because nearly all of the SOM is found on the topsoil (Chalise et al. 2019). The reserve of SOM in the majority of agricultural soils has been diminished because of an increase in soil erosion. The functionality of soil, its ability to supply vital ecosystem services, and the health of the soil could all be adversely affected by a significant reduction of SOM content. Therefore, recovering SOM content in soils of agroecosystems could reverse the current rate of degradation, boost ecosystem services, and expand UN Sustainable Development Goals (Rattan 2020). While rehabilitating the environment, a boost in SOM content could also partially substitute for the application of chemical fertilizers and additional irrigation (Rattan 2020).

2.3.4 Anthropogenic Effect

The severity of contamination in the soil on a global scale and several restrictions which includes those caused by stress (abiotic and biotic) are the main risks to demand for food and food security given the increasing natural and anthropogenic activities, and these will likely disrupt food security in the coming years (Riaz et al. 2019). Due to reliance of agriculture on chemical fertilizers, the irrigation of wastewater, fungicides, the use pesticides as well as the quick development of industries, the concentration of toxic metal(loid)s and organic contaminants in arable land has risen and this has negative impacts on the soil-plant environmental system (Bansiwal and Maheshvari 2018). The lingering contaminants lower crop output and impairs soil productivity. The economic and social conditions around the world are being negatively impacted by this problem.

Clinical problems within biological networks (of animals and people) can arise from the accumulation of inorganic and organic pollutants in edible or inedible parts of commercially significant plants and crops grown in non-polluted soil (Li et al. 2018).

3 Different Monitoring Indicators of Soil Quality

Soil quality indicators are used to evaluate how well the soil functions and can be determined using a composite set of quantifiable physical, chemical, and biological properties related to functional soil processes. A study by Terashima and Mihara (2020), investigated the physical, chemical, and biological properties of the soil of two farms with different practices and the result indicated a significant difference between the microorganisms, but could not be identified with physical and chemical properties. This section provides an introduction to different monitoring indicators of soil qualities. The indicators for evaluating the health and quality of soil fall within three categories; this encompasses physical, chemical, and biological indicators.

3.1 Physical Indicators

The physical markers of soil quality show how well the ecosystem can absorb, store, transfer, and deliver water, oxygen, and nutrients. According to a study conducted by Ahmad et al. (2022), the soil's capacity to provide plants with a suitable environment, including moisture, air, and support, is influenced by its physical properties. To assess soil quality, various physical indicators are employed, such as pore size distribution, aggregate stability, saturated hydraulic conductivity, texture, infiltration rate, bulk density, and surface crust (Loganathan and Navendrian 2014). In a study conducted by Irmal et al. (2018), field experiments were undertaken to

quantify the influence of cover cropping on soil physical properties. The properties examined in the study included Permanent Wilting Point (PWP), Field Capacity (FC), soil-water holding capacity (SWHC), bulk density (rb), saturated and unsaturated hydraulic conductivity (Ks and Kus, respectively), and infiltration rates. These properties were measured and compared across four different land cover treatments. They discovered that the soil's physical properties were unaffected by incorporating rotational cover crops into row crop cultivation, and there was no significant difference between the treatments for all seasons. They concluded by indicating that combining cover crops into various grain rotations reduced the infiltration rate but could not sufficiently determine if cover crops are responsible for altering soil physical properties. Physical indicators of soil quality include measures of:

a) Soil bulk density

The bulk density of soil indicates the mass of a certain volume of soil. Instead of exceeding a predetermined threshold, bulk density has been proposed as a soil quality measure for British soils in relation to trends over time. The density of the soil in large quantities influences numerous soil properties, such as infiltration, available water capacity, soil porosity, rooting depth, soil microbial activity, root proliferation, and nutrient availability (Corstanje et al. 2017). In a study conducted by Indoria et al. (2020), it was revealed that the bulk density was dependent on available macronutrients and micronutrients in the soil, with regards to organic matter, and that it decreases as the total macronutrient or total micronutrient contents in the soil increases.

b) Soil texture

Soil texture is determined by the proportion of three particle sizes of sand, silt, and clay. It has a significant role in the processes of soil deterioration and water transport, regulating the quality and productivity of the soil (Yu et al. 2020). It has an impact on a variety of soil characteristics; including how well the soil supplies water, how quickly water infiltrates the soil, how easily it may be cultivated, and how susceptible it is to erosion. According to Mobilian and Craft (2021), other soil properties including bulk density, water-holding capacity, permeability, and porosity are influenced by soil texture. For instance, sand-dominated soils have higher permeability and lower capacity to hold water than soils with higher concentrations of silt and clay.

c) Soil depth

The depth of the soil affects how much soil and how much root space the plants require to meet their hydration and nutrient requirements. Generally speaking, deeper soils can provide plants with more nutrients and water than shallower soils. Additionally, soil provides mechanical support to the majority of plants (Rajakaruna and Boyd 2008). The rooting depth and water-holding capacity of the soil are strongly influenced by its depth. In deep soils with thick topsoil and superior sub-surface qualities, erosion may have little to no effect on productivity. Water availability can be influenced by soil depth in addition to soil texture and structure (Ronald 2008).

d) Infiltration

The capacity of the soil to permit water to enter and pass through the soil profile is known as soil infiltration. Water can temporarily be stored in the soil by infiltration, making it available to plants and other soil creatures. The main underlying factor determining infiltration is soil texture or the amount of silt and clay in the soil. Solid organic manure should be spread on the soil to increase the rate of soil infiltration (USDA 2014). One method of determining infiltration is to time how long it takes for a certain amount of water to evaporate after being sprinkled or ponded on a soil surface. The amount of water that can infiltrate into and through the soil profile is known as infiltration. Low infiltration rates in metropolitan areas brought on by compacted soil have detrimental consequences on the city's ecosystem, leading to increased flooding and poor surface water quality (Yang and Zang 2011).

e) Water holding capacity

The amount of water in a soil when its pore space is full with water and the drainage is constrained is referred to as its water holding capacity. The amount of water the soil can store for usage by plants' roots for a specific amount of time is known as the available water holding capacity (AWHC). Only poorly drained soils operate at their maximum water-holding capacity for an extended period in the natural environment. More water is stored in clay soil than in sandy soil (Nath et al. 2014).

f) Colour

The makeup of the soil is revealed by its color, which also provides insight into the conditions it is in. The amount of protein in the soil affects the color of the soil. Soils rich in humus are often dark brown to black, while those rich in iron are typically white. The color of the soil also reflects the age of the soil as well as the temperature and moisture characteristics of the climate. Cooler climates often contain topsoil that is greyish to black in color due to humus buildup. Soils in humid, warm climates tend to be more yellowish-brown to red due to the significant weathering of the soil's parent material and the hydration of ferric oxide (Amara et al. 2022). Soil color is influenced by organic matter, element concentration, moisture content, and mineral composition. Because it reflects soil characteristics and soil processes, it is a crucial diagnostic component for defining soil horizons and classifying soils (Zhang et al. 2021).

g) Temperature

Soil temperature plays a pivotal role in determining the direction of heat flow and has a significant impact on the transformation and uptake of nutrients by plant roots (Onwuka and Mang 2018). Elevated soil temperatures can lead to dehydration of clay and fragmentation of sand particles, resulting in a decrease in their respective proportions and an increase in silt content. Solar radiation has been acknowledged as the primary driver of soil temperature. Additionally, soil temperature affects soil moisture, aeration, and the availability of essential plant nutrients, thereby influencing soil characteristics and plant growth processes. It exerts control over the

physical, chemical, and biological functions of the soil, including the rate of organic matter decomposition as well as the mineralization of various organic components (Onwuka and Mang 2018).

3.2 Chemical Indicators

The ability of the soil to provide plants with nutrition is determined by its chemical conditions (Surya et al. 2018). The primary chemical markers for soil are pH, electrical conductivity, adsorption capacity, Cation exchange capacity, available Phosphorous and potassium, total Nitrogen, and soil organic matter (Thakur and Sharma 2019).

- a) **Soil reaction (pH):** The pH (acidity or alkalinity) level of the soil directly influences its chemical and biological characteristics and plays a crucial role in regulating various chemical and biological processes within the soil. The United States Department of Agriculture's National Resources Conservation Service has categorized soil pH values into different ranges: acidic (3.5), very acidic (3.5–4.4), strongly acidic (5.1–5.5), moderately acidic (5.6–6.0), slightly acidic (6.1–6.5), neutral (6.6–7.3), slightly alkaline (7.4–7.8), moderately alkaline (7.5–8.4), strongly alkaline (8.5–9.0), and very strongly alkaline (>9.0) (Oshunsanya 2019).
- b) **Cation exchange capacity:** Cation exchange capacity (CEC) is a crucial chemical characteristic of agricultural soil. Soil nutrients exist as positively charged ions when dissolved. The positively charged ions are known as cations. The nutrients which exist as cations are Sodium (Na^+), ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), hydrogen (H^+), iron (Fe^{2+}), aluminum (Al^{3+}), copper (Cu^{2+}), zinc (Zn^{2+}) and manganese (Mn^{2+}) (Arit 2016). CEC is a crucial indicator for assessing soil fertility, crop growth, and the partitioning and transportation of contaminants in the soil (Dai et al. 2018). Sharma et al. (2013) used the cation exchange capacity of the soil as well as other soil factors to successfully forecast the production of maize and soybeans.
- c) **Available Nitrogen:** Nitrogen has a positive impact on the quality of agricultural soils, due to its ability to improve soil fertility and crop-growing conditions; however, because it alters plant variety, it typically has a negative impact on the soil quality of natural soils. By changing the solubility of phosphorus in the soil, nitrogen salts may have an impact on how much phosphorus plants can absorb (He et al. 2022).
- d) **Available Phosphorous:** Between 30 and 65 percent of the total soil phosphorus is present in organic forms that are unavailable to plants, while between 35 and 70 percent is present in inorganic forms. Microorganisms in the soil and the leftovers of deceased plants and animals are sources of organic phosphorus. These organic forms of phosphorus are transformed into forms that are beneficial to plants by soil bacteria (Prasad and Chakraborty 2019).

- e) **Available Potassium:** Potassium, being the third essential macronutrient for plant growth and metabolism, plays a crucial role in various plant processes, following nitrogen and phosphorus. Insufficient potassium in plants leads to underdeveloped roots, slow growth, reduced disease resistance, delayed maturity, low seed output, and decreased yields. Potassium in the soil originates from four distinct sources. The majority of soil potassium (90 to 98%) is present in soil minerals such as feldspar and mica; however, this form of potassium is not readily available for plant uptake. The second source of potassium is non-exchangeable potassium, which accounts for 1 to 10% and is associated with clay minerals having a 2:1 ratio. Non-exchangeable potassium serves as a reserve source in the soil. The third source of potassium, making up 1 to 2% of the total, is found in the soil solution or cation exchange sites. This form of potassium is easily absorbed by plant roots and replenished by the potassium present at the exchange sites. The fourth and fifth sources of potassium in the soil are organic matter and the soil's microbial community, respectively. However, these sources contribute only a small portion of the required potassium for plant growth (Prajapati and Modi 2012).
- f) **Electrical conductivity:** The electrical conductivity (EC) of soil refers to its ability to conduct an electrical current. EC is a crucial indicator of soil fertility and nutrient availability. The presence of negatively charged sites in the soil, such as clay and organic particles, and the accumulation of cations with a positive charge determine the EC. The higher the number of cations stored in the soil, the higher the EC value. These beneficial cations for plant growth include sodium (Na^+), ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), hydrogen (H^+), iron (Fe^{2+}), aluminum (Al^{3+}), copper (Cu^{2+}), zinc (Zn^{2+}), and manganese (Arit 2016).
- g) **Soil organic matter:** This has an impact on various soil properties, including its water-holding capacity, rate of water penetration, aeration, fertility, ease of cultivation, and susceptibility to erosion. Soil organic matter encompasses a wide range of materials, from the original tissues of plants and animals to the well-decomposed mixture called humus. The organic matter present in the soil serves multiple functions. It plays a crucial role as a “nutrient reservoir” and also contributes to improving soil structure, maintaining soil quality, and reducing erosion. When plant residues are returned to the soil, different organic substances undergo decomposition. Additionally, organic matter exhibits a strong affinity for moisture (Nath et al. 2014).

3.3 *Biological Indicators*

Biological indicators of soil quality refer to the measurement or assessment of specific organisms or their activities within the soil ecosystem to gauge its overall health and functionality. These indicators provide valuable insights into the biological processes occurring in the soil and can be used to evaluate the impact of

management practices, pollution, or environmental changes on soil quality. In the last fourteen years, soil biological indicators have been given more weight in soil quality monitoring and assessment programs (Krüger et al. 2018). Due to their correlation with soil activities including microbial respiration and enzyme synthesis as well as organic matter content, terrestrial arthropod fauna, lichen, and microbial community, biological characteristics have been employed as markers of soil quality. Examples of biological indicators of soil health include microbial biomass, carbon and nitrogen, soil respiration, water content, soil enzyme, and Potential mineralization nitrogen (anaerobic incubation) (Dupont et al. 2021). Biological indicators include:

- a) **Nematodes:** Saprophytic nematodes serve as bio-indicators of soil health because they utilize a variety of advantageous strategies to improve soil functions, including ecosystem management, nitrogen enrichment through ingestion of nitrogen and the release of additional nitrogen in the form of NH_4 , which is easily assimilated, putrefaction and the distribution of bacteria and fungi to recently available organic residues (Khanum et al. 2021). According to Al-Maliki et al. (2021) *Acrobeles* and *Rhabditis* nematodes are said to have greatly increased soil fertility or nitrogen in soil. It is generally known that soil nematodes dramatically increase bacterial populations and soil nutrients.
- b) **Earthworms:** They can be utilized as bio-indicators of soil quality, since they are more sensitive to temperature changes than to impacts of moisture content. However, they found that these species (*Namalycastis indica*, *Helodrilus oculatu*, *Aporectodea caliginosa*) improved soil quality when the temperature was above 35 °C, whereas *Lumbricus terrestris* showed an inconsistent response at a temperature of more than 35 °C. As the soil quality improved at 48 °C, it was also discovered that *Namalycastis indica* exhibited a high tolerance to temperature. They came to the conclusion that soil parameters like moisture content and pH were also affected by temperature, in addition to the earthworm community (Al-Maliki et al. 2021).
- c) **Soil enzymes:** They have been used successfully as indicators of soil quality in a variety of agricultural settings. Soil enzyme activities are important biological soil quality indicators because they are operationally realistic, incredibly sensitive, integrative, and easy to measure and because they are more responsive to soil tillage and structure than other soil variables (Adetunji et al. 2017). Dehydrogenase is one of many soil enzymes that may serve as a sign of active soil microbial biomass. It is, nevertheless, extremely susceptible to seasonal variation. Beta-glucosidase, urease, amidase, phosphatase, aryl-sulphatase, and fluorescein diacetate hydrolyzing enzymes are some potential markers of soil quality. They have been suggested as prospective soil quality indicators due to their sensitivity, connection to biological activity, and quick responsiveness to changes in the soil (Al-Maliki et al. 2021).
- d) **Soil Respiration:** The rate of soil respiration reveals how well the soil can support soil life, such as plants, soil animals, and microorganisms. In the global C cycle, soil respiration is crucial for controlling the levels of atmospheric CO_2 ,

dissolved CO₂, and climate dynamics. However, soil respiration is extremely susceptible to environmental changes and is closely linked to nutrient activities like mineralization and decomposition (Luo and Zhou 2006).

4 Various Biotechnological Methods of Monitoring Soil Quality and Their Application

Monitoring of soil quality is aimed at improving agricultural productivity as well as environmental protection and sustainability. Recent biotechnology advancements have prompted the need to investigate the possibility of integrating microbial biotechnology into soil quality monitoring. The main objective of using biotechnology methods in the field of soil management is to enhance water infiltration, increase the carbon content, reduce erosion, ensure the availability of water at plant-root zone, and boost useful organisms. The following are several biotechnological methods used for monitoring soil quality, along with their respective applications:

- a) **Metagenomics:** This offers a fresh perspective on the microbial world that will not only alter modern microbiology but also have an impact on our understanding of all living things and their roles in various ecosystems. Metagenomics data can reveal a wealth of information on the genetic capacity of soil-based microbial communities to digest pollutants. Systems biology, bioinformatics, and genomics are combined to create metagenomics. By simultaneously studying the genomes of numerous creatures, it is innovative in its operation (Shrinivas et al. 2019). Nevertheless, the development of 'omic'-based technologies aimed at the global detection of genes (genomics), mRNA (transcriptomics), proteins (proteomics), and metabolites (metabolomics) presents new approaches to assess soil biological functioning. An evaluation of the mostly untapped genetic pool of soil microbial communities can be made using soil metagenomics, which entails the isolation of soil DNA, and the creation and screening of clone libraries. New biomolecules have already been discovered as a result of this strategy. The most diverse microbial communities can be found on Earth in soil habitats. The genomic, metabolic, and phylogenetic diversity that is stored in the soil metagenome has so far only been partially explored by metagenomic techniques. The development of techniques that capture the heterogeneity and dynamism of complex soil microbial communities, both over time and space, represents one of the main difficulties for soil metagenomics. Although there has been significant progress in the characterization of microbial communities by random sequencing, it is still necessary to enhance sequencing technology, lower the cost of sequencing, and develop bioinformatic tools for analyzing the massive amount of data collected. Through the application of metagenomic technology, soil microbes will continue to serve as the primary source of innovative natural products (Rolf 2005).

- b) **Metabolomics:** Metabolomics is the systematic identification and quantitation of all metabolites in a given organism or biological sample. The environmental sciences have used metabolomics for a variety of purposes, including phenotypic characterization of organisms, evaluation of plant and soil organismal assemblage responses to biotic and abiotic factors, characterization of different microbial community structures (Graham et al. 2018), and the discovery of biomarkers. Metabolomics, when applied to the soil microbiome, may offer a technique to characterize the varying activity of microbial communities, reflecting microbial genome-environment interactions and thus a cutting-edge method to evaluate soil health. By doing so, we can gain a better understanding of how communities and cells respond to abiotic and biotic stressors and gain new perspectives on how basic soil biochemical processes work (Withers et al. 2020).
- c) **Bioremediation:** Compared to the chemical and physical methods, bioremediation may remove significant portions of petroleum hydrocarbons for a relatively low cost and with far less environmental impact. In bioremediation, toxins are removed from the environment by using microorganisms like bacteria and fungi, frequently in conjunction with plants (Wu et al. 2021). The identification of novel bacterial species and genes for bioremediation is made possible by recent advancements in molecular techniques and gene mining. For the bioremediation of mercury pollution, transgenic bacteria expressing *mer* genes have been employed. JM109, a genetically modified strain of *Escherichia coli*, can extract mercury from contaminated sediment or soil. They are environmentally friendly and present an efficient method for the detoxification and removal of chemicals and heavy metals in contaminated locations (Azad et al. 2014).
- d) **Microbiome engineering:** This entails employing synthetic biology to produce microbes, plants, inhibitors, and enhancers to change the components of root exudates both qualitatively and quantitatively to transform the rhizosphere microbiome (Barkha et al. 2022). Ecological equilibrium can be restored through engineering microbiomes to change the microbiota's structural makeup. For better soil health and plant fertility, it is possible to engineer the soil microbiome to create more diversified and well-balanced microbial populations (Jee et al. 2017).
- e) **Molecular markers:** Numerous biotechnology methods have become accessible in recent years and the current benchmarks for measuring microbial community and diversity in soil are the 16S rRNA gene sequence in prokaryotes and the 18S rRNA gene and intergenic transcribed spacer region between the ribosomal genes in eukaryotes. Additionally, the broad distribution of Mesophilic archaea in soil has been demonstrated by the 16S rRNA gene sequencing of soils. According to Huera-Lucero et al. (2020), it was revealed that primers created from the 16S and 18S rDNA genes, molecular markers distinguished between fungal microbial biomass. These methods provide accurate information on the soil's condition and the environmental factors that affect microorganisms. When there is some sort of influence on the soil, the genome of bacteria sends out signals. Currently, the DNA and RNA of the many species of soil organisms are used to determine the markers of soil quality. It offers more accurate measurements of the biota, moves quickly, and has a lot of potential. By sequencing

16S rRNA genes, the composition and diversity of soil bacterial populations were evaluated. The results showed that the debris with shallow plough less tillage and treated with farmyard manure contained the maximum biodiversity. The two most common bacterial species were actinobacteria and proteobacteria (Vilkiene et al. 2021).

- f) **Biostimulants:** They are microorganisms and other substances applied to plants, the rhizosphere, seeds, soil, or other growing media with the goal of improving plant uptake of nutrients and promoting benefits to plant development, such as tolerance to abiotic stress (Kremer 2017). Environmental preservation has greatly benefited in recent years from the use of biostimulants to enhance soil quality and promote plant growth. Due to their ability to promote plant growth and increase stress tolerance, biostimulants made from seaweed extracts are highly well-liked. According to a study by Yousfi et al. (2021), the application of a rhizogenic biostimulant, made from fulvic acids, probiotics, and prebiotics, increased microbial activity, organic matter, and enzymatic activity in both types of sandy and sandy loam soils, hence increasing their fertility. With the application of the biostimulant, the soil's calcium, potassium, magnesium, and phosphorus content increased while its pH and electrical conductivity fell.
- g) **Biofertilizer:** This is a blend of dormant or active cells from beneficial strains of microorganisms such as fungi, bacteria, and blue-green algae (Aravind et al. 2021). Biofertilizers, which are microbial or soil inoculants, can enhance the fertility and productivity of plants and soil. Examples of unique microorganisms found in biofertilizers include nitrogen-fixing *Azospirillum* and phosphate-solubilizing bacteria, which make phosphorus available to plants from soil and fertilizers. Demir (2020) conducted a study to investigate the impact of microbial biofertilizer application, including *Azotobacter chroococum* and *Azotobacter vinelandii*, on the physicochemical properties of sandy-clay-loam soil in greenhouse-grown eggplant. The results demonstrated that biofertilizers could effectively improve the soil's physical and chemical characteristics, even under different irrigation levels, enhancing the overall physicochemical attributes of the soil.
- h) **Soil conditioners:** These are many kinds of organic materials, gypsum, natural deposits, and various water-soluble polymers that hold water in the soil, living plants, and microbes, which makes the soil more functional. Different types of soil conditioners include: organic soil conditioner which is made of materials from living things that increases infiltration and soil water retention, provides the substrate for biological activity, and improve aeration. Farmyard manure improves the soil's biological, chemical, and physical properties. Crop residues enhance nutrient cycling and soil conservation (Shinde et al. 2019). In a study by Ejaz et al. (2022) Potassium polyacrylamide (KPAM) (30 kg/ha), was used on wheat under water stress conditions, and it was revealed that KPAM significantly reduced the negative effect of drought stress on the wheat plant used, which lead to the conclusion that the use of soil conditioners is a promising technique for dealing with negative consequences of drought stress for achieving high crop yield. Another study by Deshesh et al. (2019), on the effect of using

some crop residues as natural conditioners on some physical and chemical properties and compared it with available N, P, and K on maize. It was revealed that the studied physical and chemical properties of the sandy soil were improved significantly with the application of all conditioners (sawdust, rice straw, and maize stalk).

- i) **Compost tea:** a container or commercial “tea brewer” that contains composted material inside a permeable bag suspended in flowing water with the goal of preserving an oxygenated environment. The fermented end product has low nutrient levels, living microbes that were cultured from the compost, and microbial metabolites that suppress plant diseases or promote plant development (Kremer 2017). The increase in organic matter and microbial diversity in compost tea-treated soils, as well as the advantages this brings, are essential features. Regardless of the usage of compost tea, its benefits for crop growth and soil fertility, while also preventing insect and disease outbreaks, make it a modern, sustainable tool compatible with organic agriculture (Eudoxie and Martin 2019).
- j) **Nanobiosensors** have also been used to find pesticides in soil samples that have been contaminated (Garba and Kumar 2020). When applied to soil quality assessment, nano biosensors have the potential to serve as innovative biological indicators by detecting and quantifying key biomarkers or indicators associated with soil health. Metals including As, Cr, Cd, Mn, and Pb may be extracted from contaminated soils using nano-materials (NMs). More recently, new avenues for pollution removal from soils have been made possible by the cooperative application of NMs and biotechnology to environmental concerns. First, the interaction between NMs and pollutants may create ideal conditions for biotechnology-based soil remediation. For instance, the addition of fullerene and graphene oxide (GO) nanoparticles increased the transport of pollutants in saturated soils, potentially increasing the effectiveness of contaminant removal by plants or microbes (Gong et al. 2018). The use of nano biosensors as biological indicators of soil quality offers several advantages, including high sensitivity, real-time monitoring capabilities, and the potential for on-site or in-field measurements.
- k) **Soil Health and Genetically Modified Crops:** Plants that are genetically modified, indirectly affect the structure, function, and diversity of soil and rhizosphere microbial communities. Genetically modified microorganisms have the potential to bio-remediate soil by more effectively degrading a variety of chemical pollutants. One of the most promising new technologies for the remediation of contaminated environmental sites is the genetic engineering of endophytic and rhizospheric bacteria for use in the plant-associated degradation of toxic compounds in soil (Joutey et al. 2013). Heavy metal removal processes have employed genetically engineered (GE) bacteria to remove Cd, Hg, Ni, Cu, and Fe. Studies have demonstrated that genetically modified crops indirectly affect the composition, diversity, and structure of microbial communities in the soil and rhizosphere. The gene *CryIAb* from the bacterium *Bacillus thuringiensis*, which produces an insecticidal protein that is released into the soil by root exu-

dition, is engineered into transgenic crops like cotton and maize to improve the soil quality (Li et al. 2022).

5 Potential Challenges of Application of Microbial Biotechnology as Bioindicators of Soil Quality

To monitor and evaluate soil quality, appropriate indicators are needed. These indicators are expected to be in line with soil management, ecological activities, climate change, merging of soil biological, physical, and chemical properties, and must be useable by different users (Lehmann et al. 2020). The existence and actions of microorganisms within the soil cannot be over-emphasized as they play a crucial role in the decomposition of organic matter and the cycling of nutrients (Brookes et al. 2008). Their activities, along with other physical and chemical factors are frequently used to qualify a healthy soil (Bossolani et al. 2021). In connecting experimental facts to the biology of soil, various indices have been used to group soil microbial populations and their activities, as measures for soil quality. Microbial diversity, activities, biomass, and soil enzymes are potential microbial biotechnological applications which are been employed as markers for assessing soil quality (Fierer et al. 2021). Notwithstanding the fact that these indices have long existed, and have proven to be very useful in most conditions, the science in which these indices are built is usually inadequate to give a clear understanding of the purpose of management implementation and policies. Kuzyakov and Blagodatskaya (2015), stated that soil microbiome activities are specific to the environmental conditions of the soil, leading to the concept of “hot spots” next to “hot moments” in the soil. “Hot spots” refer to localized areas in the soil where microbial activity is particularly intense or concentrated. Within these hot spots, microbial communities may exhibit increased enzymatic activity, nutrient cycling, and organic matter decomposition, leading to enhanced ecosystem processes. On the other hand, “hot moments” represent short periods of intense microbial activity in response to temporal changes or events. Hot moments are characterized by rapid turnover rates of nutrients, increased microbial respiration, and dynamic changes in soil processes. Quantifying soil microbial biomass, or evaluating the diversity ratio of microbes, may not provide a clear perspective for the assessment of soil quality, due to various abiotic and biotic soil factors that affect the limited involvement of microorganisms in the soil. For example, in a study by Isobe et al. (2020), a constant change in microbial populations was observed, in relation to a change in the moisture levels of the soil. Similarly, in different studies carried out by Delgado-Baquerizo et al. (2018) and Hermans et al. (2020), it was discovered that there was a steady change in the microbial population of soil, in relation to changes in the soil pH and available phosphorus in the soil correspondingly.

Also, most methods used for the estimation of microbial biomass tend to evaluate the total microbial biomass, instead of estimating the active and potentially

active biomass, which is the most important fraction that contributes to the entire biogeochemical process (Blagodatskaya and Kuzyakov 2013). In the use of microbial enzymes as indicators, enzyme activity in soils is influenced by modifications resulting from agricultural management techniques such as rotating crops, performing tillage, applying fertilizers, and managing residues or some ecological factors. The impact of these modifications was observable within practical time intervals; from a month to 12 or 24 months, far earlier than alterations in the organic matter content of the soil (Alkorta et al. 2003). The challenges involved are that the Enzyme activities related to carbon/nitrogen/phosphorus (C/N/P) metabolism may not consistently indicate the actual limiting nutrient. Increased enzyme activities can be deduced as either higher nutrient availability or decreased nutrient availability and enzyme assays of this kind measure potential activities rather than in situ activities (Nannipieri et al. 2012). Assays involving soil enzyme activity, do not always define the activities of microbes in soil samples. This complicates the interpretation of soil enzyme activities when trying to distinguish the activities of enzymes that are soil-bound, from the microbial community in the soil and those found in the root of plants (Nannipieri 1994). Similarly, the measured enzymes represent only a small fraction of enzymes with potential significance in the soil (Fierer et al. 2021). In the case of microbial diversity and biomass, different soil types have been shown to be the main determining factor when extracting the nucleic acid component of microbial communities in the soil. The presence of humic or fluvic acid, which is an enzyme-inhibiting compound is known to impede nucleic acid extraction (Thies 2007). The inability to culture most soil microbes has hindered research into the discovery of the relationships between the structure and function of intricate soil microbial communities. With the advent of next-generation sequencing (NGS), in-depth study of the composition and roles of entire microbial communities and metagenomic studies have become possible (Escobar-Zepeda et al. 2015). Nonetheless, its use and application in the understanding of indicators of soil quality, has shown potential challenges. These limitations were thought to have been circumvented by the use of serial molecular methods that allow the identification, quantification, and classification of soil microbes without the necessity of cultivation (Saleem et al. 2019). Unfortunately, these methods have failed to provide a proper understanding and connection, of the link between microbial presence, capacities, and soil functions, making the use of metagenomics in the soil a complex one. This is because the results are subject to different factors which include analysis of data, nucleic acid extraction, and sequencing (Leite et al. 2022), thereby distorting its ability to correctly identify these microbes as indicators of soil quality (Lahlali et al. 2021). Precise microbes or functional genes associated with some biological processes such as production of methane, biodegradation of cellulose, denitrification and nitrification could be identified using molecular tools. In the use of these tools in the study of microbial population and their activities based on the richness of the taxa in soil, some fundamental characteristics of the soil could hinder getting a correct result. This is well known to arise when carrying out DNA extraction or amplification of targeted genes during the PCR cycle (Sipos et al. 2010). More challenges seem to arise in the presentation of data using

metagenomics. This is based on the fact that microbial populations and their role in soil are determined greatly by certain physical and chemical factors present in that soil. The effect of these factors, on the population and activities of the microorganisms in the soil, is completely ignored (Kuramae et al. 2012). To have a better understanding of the impact of environmental factors on the microbial population and activities, proper measures and regulations are essential and should be taken into consideration by the use of independent research to determine overall trends using already available public data. In the effective study of microbial populations in soil, strict standardized procedures should be set up. Also, the frequency of sampling and the ideal sample size should be put into consideration and adopted in other for them to effectively serve as bioindicators of soil quality.

In conclusion, biotechnological strategies offer a promising avenue for the monitoring of soil quality. The identification and utilization of genetically engineered/novel microbial species to evaluate soil quality/health is proposed to be a more effective and eco-friendly means of monitoring soil quality. Incorporation of a hybrid of the 'omics' technology will enhance the efficiency of the biotechnological strategies that aim to improve possible soil biodiversity, soil productivity, as well as sustainable land management practices. Further research is needed to develop new soil monitoring tools that can be used in the field by farmers and land managers.

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The Use of Nanofertilizers as Micronutrients to Improve Marginal Soils and Crop Production



B. Ndaba, M. Akindolire, T. L. Botha, and A. Roopnarain

1 Introduction

Marginal lands refer to areas with low productivity, limited economic returns and severe agricultural limitations. They are therefore considered a threat to sustainable food production/food security and are extremely fragile i.e. prone to further degradation. Marginal lands are often considered for the cultivation of bioenergy biomass due to limitations on arable land resources, which are solely considered for food production (Kang et al. 2022). However, global arable land resources are faced by the major challenge of increasing productivity to support the ever growing populous. To ensure that the food demand is met for the projected 9 billion population in 2050, a rapid increase in global crop production by 70% is necessary (Graham-Rowe 2011; Rockström et al. 2017). That, along with the projected negative impact of climate change on agricultural productivity shows a bleak future for agriculture and meeting the food demand when considering arable lands alone for crop

B. Ndaba (✉)

Institute for Catalysis and Energy Solutions, College of Science, Engineering and Technology, University of South Africa—Florida Campus, Florida, South Africa
e-mail: NdabaB@arc.agric.za

M. Akindolire

Microbiology and Environmental Biotechnology Research Group, Agricultural Research Council—Natural Resources and Engineering, Pretoria, South Africa

T. L. Botha

Department of Zoology, University of Johannesburg, Johannesburg, South Africa

A. Roopnarain

Microbiology and Environmental Biotechnology Research Group, Agricultural Research Council—Natural Resources and Engineering, Pretoria, South Africa

Department of Environmental Sciences, College of Agriculture and Environmental Sciences, University of South Africa—Florida Campus, Florida, South Africa

production (Právělie et al. 2021). This has cast the spotlight on the world's marginal lands and the need for such lands to be considered to ensure food security. Moreover, cultivation of food crops on marginal lands is particularly promising in developing countries as it provides additional land for food production, which in turn will have a major positive impact on food security and livelihoods of poorer populations that reside on marginal lands (Lantican et al. 2003).

Several abiotic stresses may be experienced on marginal lands including low soil fertility, reduced irrigation water quality or minimal water availability, unsuitable temperatures and light intensities, amongst others. All of these factors contribute towards reduced crop productivity on such lands (Mujtaba et al. 2021). Unlocking the vast potential of marginal soils requires the improvement of soil fertility, nutrient availability, nutrient use efficiency and soil physico-chemical properties (Schröder et al. 2022). Chemical fertilizers have resulted in significant crop yield improvements in developing countries however, the applied fertilizers are poorly utilised by the plant (Adhikari and Ramana 2019). The nutrient use efficiency of N has been reported as 30–40%, P 15–20%, K 50–55% and micronutrients as little as 2–5%, due to losses of nutrients from the soil or the conversion of nutrients to recalcitrant pools (Adhikari and Ramana 2019). Moreover, chemical fertilizers can be costly for resource limited smallholder farmers resulting in low fertilizer application, which further threatens achieving sustainable crop production under marginal soils. Thus, there is a dire need of alternative sources of fertilization, which can enhance production on marginal lands. Novel soil amendments such as nanofertilizers have received growing attention, particularly for application on marginal lands, due to the multitude of benefits associated with the technology (Fig. 1). Nanofertilizers refer to particles in the nano-size range (<100 nm diameter) and bulk scale materials (>100 nm diameter) that are coated with nanoparticles, that

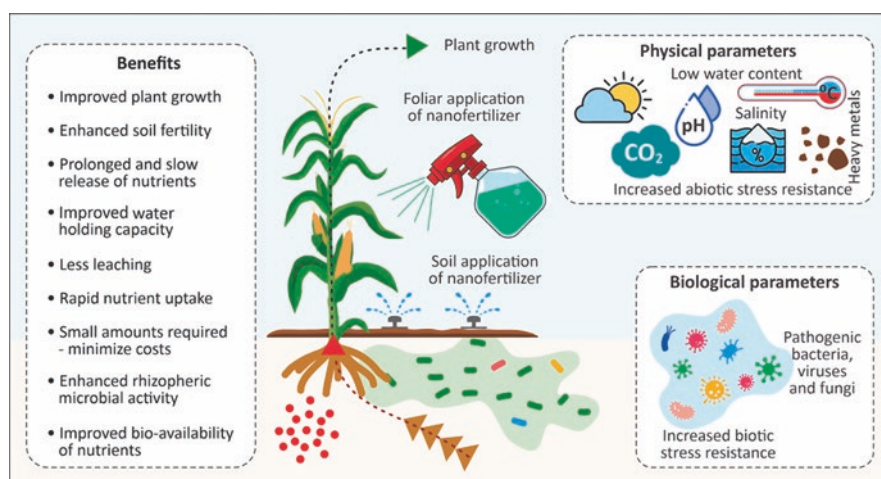


Fig. 1 Multifarious benefits associated with the application of nanofertilizers (adapted from Kalwani et al. 2022)

supply the essential nutrients that are required for plant growth (Raliya et al. 2017). These types of fertilizers are particularly promising due to their elevated use efficiency and target delivery, which avoids wastage thereby reducing costs and negative environmental implications associated with nutrient leaching (Adhikari et al. 2010). Moreover, nanofertilizers may be synthesized using substrates such as agricultural waste, which are abundantly available, making them both environmentally friendly and cost effective (Lateef et al. 2019). Nanofertilizers are generally categorised into three groups i.e. macronutrient-based, micronutrient-based and biofertilizer-based nanofertilizers (Babu et al. 2022).

Micronutrient-based nanofertilizers are of particular promise in marginal soils due to the propensity of such soils to be low in fertility, contain low soil organic matter content and be of coarse textures, which impacts negatively on the availability of micronutrients to plants (Fageria 2016). These nanofertilizers are applied to plants by either soil or foliar application (Fig. 1) and are proposed to improve bio-availability of micronutrients, improve dispersion and solubility and reduce soil fixation and absorption, even under marginal soils (Liu and Lal 2015; Qureshi et al. 2018). These nanofertilizers also provision several additional advantages when compared to conventional chemical fertilizers. The delivery system used for nanofertilizers differs from that of conventional fertilizers and is one of the contributing factors towards improved nutrient use efficiency. Nanofertilizers provide controlled, gradual nutrient release to plants due to the connecting or wrapping of the nanomaterials in the fertilizer formulation (Chen et al. 2018). This ensures that nutrients are available to the plant for a longer duration thereby impacting positively on plant growth (Chen et al. 2018). Additionally, the minute size and large surface area of nanoparticles enable ease of penetration and nutrient usage by plants in comparison to conventional chemical fertilizers. Moreover, the nutrient requirement of the specific crop can be catered for with minimal wastage using nanofertilizers. Comparatively, conventional chemical fertilizers may be over applied leading to soil salinity, which is of greater concern in already saline soils of marginal lands (Mujtaba et al. 2021).

Overall, the application of micronutrient-based nanofertilizers to improve crop production on marginal lands holds a lot of promise in comparison to conventional chemical fertilizers. This chapter aims to outline essential micronutrients and their roles followed by a synopsis of applications of nanofertilizers on marginal lands and the response of crops exposed to biotic and abiotic stresses to the application of nanofertilizers. The environmental implication of nanofertilizer application and recommendations are also discussed.

2 Essential Micronutrients and Their Roles

After macronutrients, the most important requirement to maintain balanced crop nutrition, high crop productivity and increased nutritional quality of agricultural crops is micronutrients (Kumar et al. 2022). Although micronutrients are needed in

relatively small amounts compared to macronutrients, both are equally necessary for optimal physiological and metabolic processes in plant. Most micronutrients function in plant metabolism as cofactors of metal-containing proteins known as metalloproteins that catalyse electron transport reactions and as regulators of specific enzymatic reactions (Yruela 2013; Castillo-González et al. 2018). An inadequate supply of most micronutrients contributes to a decrease in the catalytic function of critical micronutrient-dependent enzymes, thus inducing various metabolic alterations and structural and compositional anomalies with a consequent impact on overall plant health (Jatav et al. 2020). Thus, the critical roles of trace elements not only in plant growth and therefore agricultural production but also in human and animal nutrition cannot be overemphasized. The following section describes the benefits of essential micronutrients in agriculture with respect to their role in improving crop productivity.

2.1 Iron

Iron is the fourth most abundant element in the Earth's crust; however, it is the third most limiting nutrient for plant growth and metabolism, particularly in calcareous soil (Frey and Reed 2012). Calcareous soils generally have a high pH, which promotes the formation of insoluble ferric hydroxide complexes and thus makes Fe inaccessible to plants even when it is present in the soil. Furthermore, elevated bicarbonate concentration, high relative humidity, poor aeration and soluble salts and nitrate, which often prevail in this soil type, exacerbate Fe limitation by reducing the solubility of iron in soil solution (Shahsavandi et al. 2020).

As with other transition metals, iron (Fe) demonstrates the unique electrochemical property of exhibiting variable oxidation states. The oxidation states (Fe^{2+}) and (Fe^{3+}) are often the prevalent oxidation states, however, other high valent intermediates generated during catalytic cycle of some iron enzymes are known. Based on these unique redox properties, Fe has great significance in the electron transport chains of many biological processes. For example, Fe plays a key role in oxidation and reduction reactions associated with photosynthesis where the element occurs as Fe-heme, non-heme and Fe-Sulphur clusters for photosynthetic enzymes in the thylakoid membranes of chloroplasts (Kroh and Pilon 2020). In fact, almost 80% of the cellular Fe in leaf cells is found in the chloroplast as an essential part of cytochrome (heme proteins) and ferredoxin (Fe-S proteins). Both enzymes play a vital role in electron transport systems in the chloroplast and are therefore important for cellular energy production (Ishka et al. 2022). In the absence of an adequate supply of Fe, the catalytic functions of key metalloenzymes in the chloroplast including Fe-S proteins as well as copper-containing plastocyanin are reduced (Kroh and Pilon 2020). Iron is also required for chlorophyll biosynthesis, a lack of which is associated with chloroplast degeneration and reduced chlorophyll synthesis leading to chlorosis in leaves and consequently impaired photosynthesis (Kroh and Pilon 2020).

Similarly, Fe potentially plays a crucial role in nitrogen assimilation as a metal cofactor of enzymes of the reductive assimilatory pathway enzymes including nitrate reductase (NR) and glutamate synthase (GOGAT), both requiring Fe as Fe-heme group or Fe-S cluster (Schmidt et al. 2020). Iron deficiency results in a lack of activity in the Fe-requiring pathway related to nitrogen metabolism, which compromises plant productivity. The microelement stimulates the activity of other vital enzymes that participate in key metabolic processes such as respiration (cytochrome) and redox balance (catalase, peroxidase, SOD) (Kroh and Pilon 2020).

2.2 Zinc

Zinc does not exist in its pure elemental form but is usually found in the combined state as oxides, sulfides and silicates (Broadley et al. 2007). Zinc is typically the third most abundant micronutrient in plant cells after iron (Fe) and manganese, indicating its key role in cellular processes. It functions mainly as a metal cofactor of enzymes and is the only metal represented in all six enzyme classes (oxidoreductases, transferases, hydrolases, lyases, isomerases, ligases (Marschner 2011). In plants, Zn is necessary for the activity of alcohol dehydrogenase, Cu-Zn-SOD, carbonic anhydrase and RNA polymerase. Alcohol dehydrogenase together with pyruvate decarboxylase aids fermentation and low oxygen tolerance of plants through the mediation of the reversible oxidation of alcohols to aldehydes as well as ketones (Ventura et al. 2020). Genetic evidence supports the need for AD in fermentative metabolism since adh mutant displayed reduced hypoxia tolerance whereas when overproduced, the enzyme confers enhanced anoxia tolerance (Ventura et al. 2020).

Cu-Zn-superoxide dismutase is a Zn-containing metalloprotein that catalyses the dismutation of reactive oxygen species (ROS), including superoxide and hydrogen peroxide (Castillo-González et al. 2018). Consequently, Cu-Zn-SOD is key to the establishment of ROS detoxification and, therefore, protection against oxidative stress in most plant cells exposed to oxygen. Generally, induced production of ROS proceeds through the transfer of electrons across the membrane to molecular oxygen which results in the generation of superoxide. This process is catalysed by NAD(P)H-oxidizing systems localized in different cell compartments. Zn plays a structural role by controlling the production of toxic oxygen-free radicals through interference with NADPH oxidation and the removal of oxygen radicals. Therefore, with Zn deficiency, therefore, there is an increase in toxic O₂ production as well as an increase in membrane permeability, resulting in cell electrolyte leakage and membrane peroxidation. Thus, low levels of Zn in plants cause induction of oxidative stress, which may be attributed to a decrease in Cu-Zn-SOD activity (Castillo-González et al. 2018). The roles of Zn in plant defense against pathogens and drought stress by regulating various physiological and biochemical mechanisms have also been described (Hassan et al. 2018).

A further function of Zn is its role in the photosynthetic fixation of CO₂ due to the enzyme β -carbonic anhydrase, which is a Zn-requiring metalloenzyme. This

enzyme is a major component of leaf protein that is localised in the stroma of the chloroplast and rapidly catalyses the interconversion of carbon dioxide and water into the bicarbonate ion (HCO_3^-) (Castillo-González et al. 2018). Evidence suggests that there is a close relationship between carbonic anhydrase (CA) and Zn in plant physiology and that Zn deficiency reduces the CA content in some plants (Escudero-Almanza et al. 2012). In addition, Zn also acts as an important cofactor of Zn-finger proteins that regulate transcription via site-specific interactions (Yruela 2013). Other enzymes such as aldolase and fructose-1, 6-bisphosphatase that participate in carbohydrate metabolism also depend on Zn for their activities. Fructose-1, 9-bisphosphate catalyses the excision of fructose 1, 6-bisphosphatase into two trioses. With Zn deprivation, the activities of these enzymes become depressed, leading to the accumulation of carbohydrates in plant leaves (Castillo-González et al. 2018).

In Zn-deprived plants, the concentrations of proteins are reduced while those of amino acids are increased, but when Zn is restored, the effects are reversed with protein synthesis being rapidly enhanced. Zinc contributes to plant development by its indirect action on phytohormones such as auxin also known as indole acetic acid (IAA) metabolisms. It activates tryptophan synthase, which facilitates the synthesis of tryptophan, the precursor of IAA. Therefore, the amount of IAA decreases with Zn starvation since tryptophan synthesis is impaired (Castillo-González et al. 2018).

2.3 Copper

Generally, besides the presence of adequate levels of nutrients, availability in most soils is governed by other soil factors that affect Cu solubility and fixation such as soil pH, organic matter content and the presence of other soil minerals. Soil pH mainly affects solubility and therefore availability, as the amount of soluble Cu increases in soil pH below 7.5 and decreases at a higher pH, but occasionally the opposite may be true. Some marginal soils, in the form of highly weathered soils and sandy soils with characteristic low pH, are often found to be deficient in organic carbon, as well as micro- and macronutrients (Fauzi et al. 2013). The low clay and organic matter contents associated with these soils apparently have a great influence on both soil buffer capacity and the ability to retain dissolved plant nutrients. Therefore, such marginal soils are more likely to have a low Cu concentration and, as a result, may display a high degree of deficiency.

Copper is a redox-competent transition element that exists mainly as Cu^{1+} and Cu^{2+} , as such drives a myriad of redox processes and electron transport reactions (Ishka et al. 2022). The most well-known redox function of Cu is as a co-factor in electron transport in photosynthesis. Cellular Cu is actively accumulated in the chloroplast bonded to plastocyanin, an electron carrier for the photosynthetic machinery located in the thylakoid lumen of the chloroplast (Tapken et al. 2012; Shahbaz et al. 2015). Cu deficiency affects pigment and lipid biosynthesis and consequently, impacts chloroplast ultrastructure thus negatively influencing the photosynthetic efficiency (Broadley et al. 2012). Thus, in Cu-deficient plants, there is a reduction

in the rate of photosynthesis and carbohydrate production, which subsequently leads to growth retardation. Another key Cu protein is Cu-Zn-superoxide dismutase (SOD) localized in the stroma of chloroplast and cytoplasm as well as peroxisomes, where it participates in scavenging of reactive oxygen species (Broadley et al. 2012).

Within the respiration systems, Cu is required for the activity of cytochrome c oxidase which plays a crucial role in the mitochondrial electron transport chain and is therefore important for cellular energy production (Ishka et al. 2022). In particular, two Cu atoms and two heme Fe are required for the assembly of the active oxidase complex in mitochondria (Broadley et al. 2012). Copper is required as a constituent of other oxidases such as ascorbate oxidase that catalyses the oxidation of ascorbic acid to L-dehydro ascorbic acid; diamine oxidases, a flavoprotein that catalyses the aerobic degradation of polyamines. Polyphenol oxidases or catechol oxidases facilitate the oxygenation reactions of plant phenols for the biosynthesis of lignin and alkaloids as well as the formation of melanotic substances by injured plant tissue (Broadley et al. 2012). Therefore, Cu deficiency strongly inhibits polyphenol oxidase activity, contributing to an accumulation of phenolics and a decrease in the formation of melanotic substances. The reduced activity of phenol oxidase with low Cu conditions might be partly responsible for the delay in flowering and senescence associated with Cu-deficient plants (Broadley et al. 2012).

Additionally, a depression in cytochrome C activity and increased production of ROS in Cu-deficient plants can lead to reduced cellular energy levels and hinder pollen germination (Rahmati Ishka and Vatamaniuk 2020). Cu inhibition of lignification in Cu-deficient plants is attributed to a direct role of at least two Cu enzymes involved in lignin biosynthesis: Polyphenol oxidase catalyses the oxidation of phenolics as precursors of lignin and diamine oxidase provides the H_2O_2 required for oxidation by peroxidase. Accordingly, the activities of both enzymes are lowered in Cu-deficient tissues, and phenolics accumulate (Broadley et al. 2012).

2.4 Manganese

Manganese solubility and subsequent availability increases as the soil pH increases, but with an increase in organic matter content, there is a reduction in the amount of exchangeable manganese. Thus, manganese deficiency is prevalent in most poorly drained alkaline soils with a pH above 6. Manganese is an indispensable part of the photosynthetic machinery called the photosystem II water-splitting proteins (Alejandro et al. 2020). Photosystem II is a large pigment protein complex comprising more than 20 protein subunits and a key driver of the light reactions of photosynthesis in the thylakoid membranes of photosynthetic organisms, the PS II proteins function to activate electron transfer and water splitting reaction when stimulated by light. This light-induced water oxidation is catalysed by the manganese-containing unit known as the Mn_4O_5Ca cluster within the O_2 -evolving complex (OEC) in photosystem II.

In addition to its role in photosynthesis as a constituent of metalloenzymes involved in water oxidation, it is also a cofactor of an important antioxidant enzyme, superoxide dismutase. Along with other metalloenzymes such as Zn and Cu, Mn is part of the structure of an important superoxide dismutase also known as ROS quencher, which participates in protecting plant cells from the damaging effects of oxygen and free radicals in the mitochondria and peroxisomes (Schmidt and Husted 2019).

Manganese may also have functions related to N metabolism and assimilation through its effect on key N-metabolism enzymes such as nitrate reductase (NR), glutamate dehydrogenase (GDH), glutamine synthase (GS) and glutamic-oxaloacetate transaminase (GOT). Nitrate reductase is a molybdoenzyme that facilitates the reduction of nitrate to nitrite for the production of proteins in crop plants, and its activity is lower with Mn deficiency. Deficiency in Mn has been associated with restricted uptake and transport of nitrate, the depressed activity of N-metabolism enzymes, and thus reduced the production of chlorophyll and soluble protein and inhibited the growth of maize seedlings (Gong et al. 2011). Manganese has several very important roles in the plant, including functioning as an activator or cofactor of at least 35 enzymes (Alejandro et al. 2020).

2.5 Boron

The bioavailability of B in soil is similar to that of other micronutrients, which increases with increased acidity, but decreases with increased leaching associated with sandy soil and low organic matter content. The most well-known role of B is its involvement in cell wall formation. The localization of a large proportion (over 90%) of cellular B in the cell wall and its association with pectin as well as the effect of B on cell wall elongation suggest that B plays a critical role in the cell wall structure of higher plants (Brdar-Jokanović 2020).

An effect of B on the cell wall structure is related to its ability to bind to rhamnogalacturonan II (RG-II) and form a borate-RGII complex, which is vital to the structure and function of the cell wall (Brdar-Jokanović 2020). In the plant cell wall, boron links two pectic domain rhamnogalacturonan II (RG-II) chains together to form a dimer and thus contributes to the reinforcement of cell adhesion. Formation of B complex has been described as a mechanism of cross-linking of cell wall polymers, especially pectin polysaccharides with the aim of contributing to mechanical strength and physical properties of the cell wall (Brdar-Jokanović 2020).

With a reduction in B supply, there is a reduction in the RG-II complex in pumpkin, causing abnormal cell wall formation (Ishii et al. 2001). B deficiency primarily affects cell wall ultrastructure with early symptoms including structural abnormalities, especially in the cell wall and middle lamella in castor bean plants (González-Fontes et al. 2008). Deficiency may hinder root elongation by inhibiting cell enlargement and cell division in the growing zone of root tips. Furthermore, the

importance of B in supporting upright growth in vascular plants and for lignification of secondary walls has been described (Brdar-Jokanović 2020).

In addition to its structural role in stabilizing cell walls by cross-linking of RGII complexes, B is an important regulatory compound. Boron regulates the transcription levels of various hydrolytic enzymes that function in cell wall loosening for cell elongation such as XTHs, expansins, pectin methylesterases, and pectin lyases in *Arabidopsis* roots (Camacho-Cristóbal et al. 2011). Thus, with B deficiency, gene transcription concentrations for these enzymes are reduced, affecting cell wall synthesis and modification (Camacho-Cristóbal et al. 2011).

In most plant species, B deficiency limits reproductive growth more than vegetative growth. Although the exact roles in reproductive growth are unknown, a regulatory role for B in pollen germination and pollen tube growth is suggested (Wang et al. 2003). The requirement of B for proper germination of tube growth has been demonstrated by both in vivo and in vitro studies (Nyomora et al. 2000; Wang et al. 2003). It has been shown that deficiency significantly reduces the germination rate of pollen grains, resulting in poor pollen tube development.

2.6 Molybdenum

Molybdenum deficiency is common in many sandy and acidic tropical soils, where weathering and leaching can contribute to limiting the total amounts of trace elements in soils. Availability is often increased by adding lime to raise the pH or foliar spray, seed priming, seed coating and the addition of fertilizer in soils with low total Mo content.

Molybdenum has long been recognised as an essential micronutrient for higher plants, animals and microorganisms (Novotny and Peterson 2018). Although, Mo alone is biologically inactive, but when complexed with a unique organic pterin acquires a remarkable biological activity and thereby forms Mo-cofactor (Moco). Once incorporated as a pterin complex, Moco binds to Mo-dependent enzymes (molybdoenzymes) in order to participate in various key redox processes in the global carbon, sulphur and nitrogen metabolism (Tejada-Jiménez et al. 2013). In plants, the most prominent molybdoenzymes are nitrate reductase (NR), sulphite oxidase (SO), Xanthine dehydrogenase (XDH), aldehyde oxidase (AO) and amidoxime reducing component (ARC) (Kruse et al. 2010).

Among Mo-dependent enzymes, NR represents a cytoplasmic enzyme required for the reduction of nitrate to nitrite for inorganic N assimilation (Fischer et al. 2005). With Mo as a cofactor, NR catalyses the first step of the nitrate reduction pathway to produce nitrite, which is further, reduced to ammonium or reduced to nitric oxide by Silaghi-Dumitrescu et al. (2012). Therefore, both Mo and nitrate as the substrate influence NR activity, however, in Mo-deficient plants restoration of NR activity occurs faster with Mo resupply than with nitrate.

Given the various important roles of micronutrients in plant growth and development as well as the tendencies of a greater part of marginal soils to be deficient, it is

essential to include micronutrient fertilisers in fertilising practices. Micronutrient mineral fertilisers are commonly used to correct deficiencies and improve soil nutrient status, but new technologies involving the application of micronutrient nanofertilizers offer a promising approach to address soil infertility and boost plant productivity (Ndaba et al. 2022).

3 Nanofertilizer Application on Marginal Soils

Nanotechnology spans a wide range of scientific disciplines with new strategies based on molecular self-assembly to create new materials with nanoscale dimensions of primary size between 1 and 100 nm which can be achieved by manipulating matter at the atomic level. The synthesis of nanomaterials can either follow the bottom up approach by assembling single atoms into nanomaterials or top down approach by breaking large materials in nanosized ones allowing for bulk production (Abid et al. 2022). As nanotechnology enters the agricultural sector, a novel type of fertilizer known as a “nanofertilizer” containing nanomaterials has emerged. Nanofertilizers have unique physical and chemical characteristics that improve the transport and uptake of nutrients by plants (Mejias et al. 2021). By producing required micronutrients at the nanoscale, the ions required (zinc, calcium, iron, and magnesium) needed to promote plant growth can slowly be released by dissolution from the nanocore thereby reducing excessive leaching and waste compared to traditional fertilizers. These nanomaterials can increase the effectiveness of fertilizer application, decrease nutrient losses by decreasing leaching, and supply specific nutrients to certain plant tissues (Kalwani et al. 2022).

Many technological advances exist for using nanofertilizers to improve fertilizer use efficiency. The solubility and availability of nutrients in the soil can be improved by nanoparticles’ small size and large surface area, making them more available to plant roots and pores in foliage. This can enhance nutrient uptake, lessen leaching or volatilization losses, and enhance plant growth and output (Sheoran et al. 2021). Second, nutrients can be released from nanofertilizers in a targeted and regulated manner, for example in response to particular soil or plant requirements. The frequency and volume of fertilizer applications can be decreased by functionalizing nanofertilizers with organic or inorganic coatings that can delay their release and improve their persistence in the soil. However, the type of soil and its characteristics, as well as the characteristics of the nanomaterials, may affect how effectively nanofertilizers reduce leaching. The size, surface charge and density of soil can affect the mobility of nanomaterials in soil; clay is known to cause higher mobilization of nanomaterials in soil as they are able to move in capillary water while large soil tends to trap larger agglomerates for longer. By reducing runoff, this can avoid overfertilization, improve nutrient usage efficiency, and lessen environmental pollution. Third, in order to offer numerous advantages in a single application, nanofertilizers can be functionalized with other substances, such as insecticides or growth regulators (Nongbet et al. 2022).

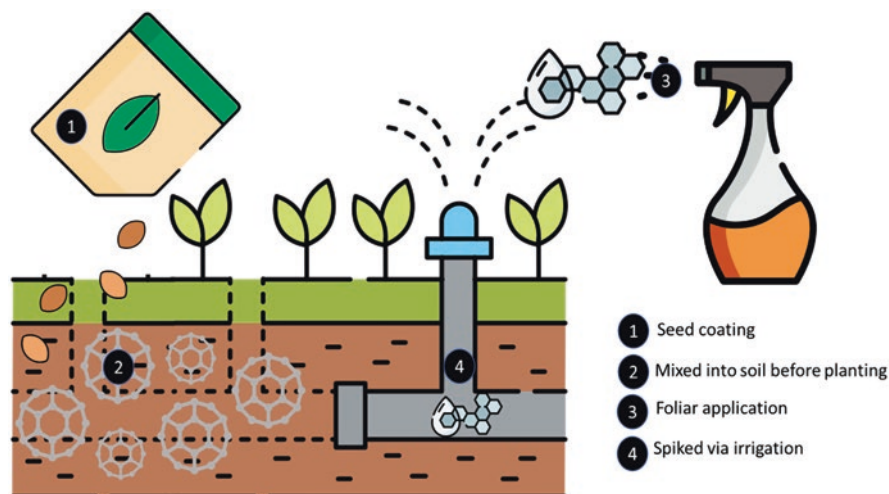


Fig. 2 Application methods of nanofertilizers in agriculture

There are several ways to apply nanofertilizers (Fig. 2). To improve nutrient uptake and the growth of the developing plant, seeds can be coated with a thin layer of nanofertilizer (Nongbet et al. 2022). Spraying a nanofertilizer solution onto a plant's leaves, where the nutrients can be easily absorbed and utilized by the plant, is known as foliar spraying (Wani et al. 2019). Prior to planting, the nanofertilizer is mixed with the soil to allow the nanoparticles to gradually release nutrients into the soil. By using spiked irrigation, it is possible to apply a nanofertilizer solution that can more effectively and uniformly distribute nutrients throughout the soil. The crop type, growth stage, soil condition and type, as well as the properties of the nanofertilizer may affect the application technique. The specific nutritional requirements, soil and plant features, and environmental factors unique to the agricultural system all affect the type of nanofertilizer that is selected. However, prior to usage in agriculture, it is critical to assess the effectiveness, safety, and sustainability of each form of nanofertilizer ensuring utilization of the proper application rates and adhering to suggested standards (Mejias et al. 2021). The rate of photosynthesis and transpiration is slowed down by several of the commonly bioaccumulated nanoparticles, including copper oxide, lanthanum oxide, cerium oxide, and nickel oxide. In addition, they can negatively affect the growth and survival of cellular and subcellular organisms associated with plant growth and metabolic functioning (Kumar et al. 2018).

3.1 Characterization of Nanofertilizers

Assessing the physical and chemical characteristics of nanofertilizers helps us understand their composition, structure, and environmental behavior. This encompasses techniques such as X-ray diffraction, scanning electron microscopy (SEM),

transmission electron microscopy (TEM), Fourier-transform infrared (FTIR) spectroscopy, dynamic light scattering (DLS), and zeta potential analysis. These methods can be used to analyze nanofertilizers' size, shape, surface charge, chemical composition, stability, reactivity, and potential interactions with soil and plants (Kaliva and Vamvakaki 2020). Such characterization is crucial for determining the efficacy and safety of nanofertilizers and specific properties which will affect their safety are outlined below (Mejias et al. 2021). The major issue associated with interactions of nanomaterials in soil is the sheer size of the nanomaterial compared to the soil particles and visualization tools are no longer feasible. For metallic nanomaterials techniques which can detect the metal are used to identify distribution in soil.

Nanofertilizers have several unique properties that distinguish them from conventional fertilizers, if any of these properties are altered, they would affect the safety and efficacy of the nanomaterial. Some of these properties include (Ikhamyies 2014; McClements 2015; Kaliva and Vamvakaki 2020):

- **Small particle size:** Nanofertilizers typically have particles where at least half of the particles in the number size distribution are between one and one hundred nanometers (nm) in size, which can increase their solubility, reactivity, and mobility in the soil and plant tissues.
- **High surface area:** Nanoparticles' high surface areas can increase their interaction with soil and plant surfaces, enhancing the efficiency of their nutrient delivery and uptake.
- **Surface charge:** Nanofertilizers can have positively or negatively charged surfaces, which can have an impact on how effectively they adhere to surfaces and interact with other elements of the soil and plants.
- **Targeted and controlled release:** Nanofertilizers can be engineered to release nutrients according to the needs of the plant or specific soil conditions, reducing overfertilization and pollution.
- **Functionalization:** Nanofertilizers can be functionalized with other substances, such polymers or surfactants, to improve their stability, solubility, or other properties, bringing about a range of benefits in a single application.

Among the frequently employed nanofertilizers are:

Nanoscale nutrient salts: Inorganic nanoparticles of vital nutrients like nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur are employed as nanofertilizers and are known as "nanoscale nutrient salts." These nanoparticles can increase the solubility and availability of nutrients in the soil and plant tissues and typically range in size from 1 to 100 nanometers. These nanoparticles' small size enhances their surface area, which can improve their soil reactivity and mobility and increase their uptake by plants. Many techniques, such as chemical precipitation, hydrothermal synthesis, and the sol-gel method, can be used to create nanoscale nutritional salts. An emerging technology that has demonstrated promising results in improving nutrient use efficiency and lowering environmental pollution in agriculture is the use of nanoscale nutrient salts as nanofertilizers (Das et al. 2021). Micronutrient iron applied at low concentrations (10 mg/L) via foliar application to maize and rice crops has been shown to significantly enhance seed germination, increase

chlorophyll content and produce higher crop yields (Perna et al. 2021). Similar results were seen in peanut yield after low concentration zinc oxide micronutrient application; however dose dependent effects were noted where higher concentrations of application had lower yield although still higher than bulk metal application (Prasad et al. 2012). Co et al. (2016) evaluated the effect of copper and aluminium oxide nanoparticles on induced shrinkage of soil. It was reported that the nanoparticles have the potential to be used as soil additives where soil shrinkage is severe.

Nanocoated fertilizers: Fertilizers or seeds that have been conventionally coated with a thin layer of nanoparticles can increase their effectiveness and lessen nutrient losses in the soil. Depending on the particular needs of the crop and soil, the nanoparticles utilized for coating may be formed of different substances, such as metal oxides, carbon, or polymers. The coating can provide a controlled-release system that can progressively release the nutrients in response to plant needs while also shielding the fertilizer from environmental influences like moisture, heat, or pH. The nanoparticles' small size enhances their surface area, which can improve their interaction with soil components and the plant's ability to absorb nutrients. The use of fertilizers with nanocoatings can also minimize the loss of nutrients by leaching, volatilization, or fixing in the soil, resulting in a more effective use of fertilizer and a reduced ecological consequence. Nanocoated fertilizers are a promising technology for sustainable agriculture because their characteristics can be modified to meet the unique requirements of the agricultural system (Fraceto et al. 2016). For instance, Zareabyaneh and Bayatvarkeshi (2015) studied the effect of slow-release of sulphur coated nano-nitrogen chelate (SNNC) on nitrate leaching as well as distribution in soil while growing potato. The treatments reduced nitrate leaching levels by approximately 40% when compared to Urea fertilizer application, while potato yield increased by 59.61%.

Nanoencapsulated fertilizers: Nanocapsules have the advantages of stability, precise targeting, controlled sustained release, and minimal side effects. They are nanodimensional shells constructed of nontoxic polymeric material containing a liquid core which can provide a controlled-release mechanism of encapsulated nutrients. Nanoencapsulation's controlled-release process can also lessen the chance of over-fertilization, which can cause environmental damage and financial losses. In various agricultural settings, nanoencapsulated fertilizers have demonstrated remarkable results in increasing crop productivity and lowering environmental pollution. The performance of conventional fertilizers can be improved by the material interacting more firmly with the plant due to the higher surface tension increasing plant-uptake efficiency of nutrients and/or reducing the secondary negative effects of higher fertilizer usage. Nanofertilizers can supply one or more nutrients to the plants and promote their growth. Zeolites' nano-porous characteristics provide them a high specific surface area and a high selectivity for plant macronutrients. These nutrients can therefore be delivered gradually reducing nutrient loss and environmental concerns related to conventional fertilizers while increasing their efficacy (Iavicoli et al. 2017).

Nanocomposites: In order to improve their stability, solubility, or other qualities, nanoparticles are sometimes combined with other substances, such as polymers,

carbon, or clay, to form nanocomposites. Depending on the particular needs of the crop and soil, the nanoparticles employed in nanocomposites may be formed of various substances, such as metal oxides, carbon, or hydroxyapatite. The physical and chemical characteristics of the composite material, such as its mechanical strength, thermal stability, or catalytic activity, can be enhanced by the addition of nanoparticles. In various agricultural environments, nanocomposites have demonstrated promising outcomes in increasing crop productivity and lowering environmental pollution. The usage of a nanocomposite that contains micronutrients and the nutrients essential for plants, such as N, P, and K, enhances crop nutrient uptake and utilization while preserving soil moisture. After *Z. mays* seedlings were treated with bentonite and TiO₂ nanoparticles, the size of the holes in the root cell pores of was lowered from 6.6 to 3.0 nm (Avila-Quezada et al. 2022). The size, shape, surface charge, chemical composition of nanomaterials and the soil type, and environmental circumstances are just a few of the variables that might affect how soil and nanofertilizers interact (Kalwani et al. 2022). The stability, mobility, and bioavailability of some nanofertilizers may be impacted by interactions with soil constituents, such as clay minerals and organic matter, through electrostatic, van der Waals, or chemical processes. The features of the soil, such as pH, cation exchange capacity, and the availability of nutrients, can also have an impact on how well plants absorb nanofertilizers (Nongbet et al. 2022). More investigation is required to evaluate the possible consequences of nanofertilizer use on soil microorganisms, biodiversity, and nutrient cycling because the long-term effects on soil health and ecosystem services are currently little understood.

3.2 Plant Response to Nanofertilizer Application Under Stress

Ecosystems are affected by climate change through biotic and abiotic pressures, which disrupt the delicate environmental balance necessary for agricultural production and may result in crop loss. By controlling the supply of nutrients in the rhizosphere, nanoparticles may improve nutrient absorption and plant growth, raise plant defence mechanisms during climate changes, and extend stress tolerance. They are linked to reducing environmental pressures and improving resistance to adverse climatic eco-variables (Verma et al. 2022). Salinity, drought, floods, and heat stress are among the most prevalent abiotic stressors, whilst bacteria, viruses, and fungus are the main biotic challenges (Shalaby et al. 2022). Nanofertilizers have the potential to significantly increase plant production, both qualitatively and quantitatively, and assist grown plants under stress.

Even though vast work (Azam et al. 2022; Shalaby et al. 2022; Mahil and Kumar 2019; Toksha et al. 2021) has been directed towards the use of nanofertilizers for general crop growth, there are still few studies mainly focusing on the use of nanofertilizers for alleviating plant stresses. Hence the primary focus of this section is to discuss those studies that primarily enthralled on positive effects of nanofertilizers in alleviating the stresses while enhancing growth.

3.2.1 Abiotic Stress

Stress causes physiological and biochemical changes in plant cells that may be harmful to the development and production of the plant. The most appropriate coping method to deal with climatic stress factors and achieve sustainable output may include species and cultivars designed to withstand these difficulties coupled with nanotechnology and other climate-sensitive agricultural technologies (Kumar et al. 2022). Globally, the main abiotic stressors that restrict crop outputs are high temperatures, salinity, and water stress (Rasheed et al. 2021). Plants experience numerous physiological, metabolic and molecular changes as a result of dehydration. To counteract water stress, plants limit the amount of moisture shed via their stomata and improve CO₂ absorption to prevent photosynthetic suppression (El-Saadony et al. 2022).

Plant phenolics and antioxidant enzymes are significantly impacted by dry environments. In water stressed plants, stimuli from the roots are sent through the vascular tissue to leaf branches, influencing the cellular state (Afshari et al. 2021). Turgidity reduction in crops during drought stress are also possible. Severe dehydration may cause the protoplasm to stiffen, which would change cellular metabolism and prevent plant development. Plants' cellular metabolism, ion buildup, membrane structure integrity, and protein structures can all be significantly affected by drought. Astaneh et al. (2021) evaluated nano chelated nitrogen fertilizer on the physiological characteristics of wheat under drought stress conditions. From their findings, they observed that application of nano chelated nitrogen fertilizer resulted in photosynthesis rate and growth of wheat. Nanoiron oxide enhanced the development, yield, and quality of Glycine max seeds under water-scarce conditions, according to a research by Dola et al. (2022). In places where soybeans are grown, crop losses brought on by severe drought can be reduced by using exogenous foliar sprays, which findings showed proved to be more effective than other treatments at improving drought resistance.

In another research by Zahedi et al. (2020), the beneficial influence of SiO₂-NPs, Se-NPs, and Se/SiO₂-NPs in moderating the adverse effects of drought on the development and yield of strawberry plants has been examined. Strawberry plants cultivated under normal and drought stress circumstances had higher growth and yield metrics after being sprayed with solutions containing nanoparticles of SiO₂, Se, and Se/SiO₂ (50 and 100 mg L⁻¹). Additionally, plants had greater levels of important osmolytes including proline and glucose and maintained more of their photosynthetic pigments than other untreated plants. The relative water content (RWC), membrane stability index (MSI), and water usage efficiency (WUE) were all improved by this treatment.

Salinity stress is also one of the environmental elements that various countries claim lowers agricultural output. Because of the inadequate osmotic pressure created by salt in the soil, hindering uptake of water by plant, seeds are unable to germinate. Legume oxidative stress caused by sodium chloride (NaCl) significantly limits development, diminishes seed nutritional quality, and reduces nodulation. To lessen the impact of oxidative stress brought on by salt, plants can use a variety of

antioxidant mechanisms of defense, both enzymatic and non-enzymatic (Seleiman et al. 2022).

Certain nanofertilizers have the potential to negate abiotic stresses experienced by crops on marginal lands (Mujtaba et al. 2021). For example, nano silicon application has been shown to improve the tolerance of sweet pepper plant to elevated soil salinity (Tantawy et al. 2015). Similarly, zinc and iron nanoparticles contributed to alleviation in salt stress in *Moringa peregrina* plants (Amira et al. 2015). In separate studies, heat stress alleviation was recorded when applying zinc oxide and magnetite nanoparticles to wheat plants (Hassan et al. 2018) and water stress mitigation as well as yield improvement was evidenced in flax plants where seeds were primed with iron oxide nanoparticles (Waqas Mazhar et al. 2022). Copper nanoparticles were applied topically to a tomato crop that was under salt stress in a study by Pérez-Labrada et al. (2019). In comparison to the control, the treatment enhanced the Na⁺/K⁺ ratio, boosted performance, and raised the amount of phenols in the leaves and glutathione and vitamin C in the fruit. The researchers came to the conclusion that foliar spraying tomatoes with copper nanoparticles under salinity seemed to increase stress tolerance through enhancing the plant's antioxidant defenses.

For plants to recover from abiotic stress, a number of nanoparticles are engaged in diverse plant systems. For example, it has been discovered that compounds based on silicon are active throughout the growth and defense of plants. Silicon-based nanoparticles have been reported to be able to reduce abiotic stressors due to their use in several agricultural sectors (Jeelani et al. 2020). These nanoparticles can enhance metal ion absorption, stabilization, as well as nutritional element balance, tolerance to abiotic stress, and antioxidant enzyme activation. To promote plant quality and development, these systems all operate together (Basavegowda and Baek 2021).

Nanoparticles improve development and stimulate the function of certain anti-oxidative enzymes, that are frequently suppressed on marginal lands. Silver nanoparticles, on the other hand, have a concentration-dependent impact on stressed plants. Sharma et al. (2012) determined that a 50-ppm dosage of silver nanoparticles was optimal for enhancing development and antioxidant status of maize, beans and mustard under oxidative stressed environments. Under visible and ultraviolet light stressed irradiation, titanium nanoparticles increased photosynthesis, photosystem II photoreduction efficiency, oxygen synthesis, and chloroplast photophosphorylation for the spinach plant to convert energy ADP to ATP.

Moreover, zinc nanoparticles are crucial for the survival of plants in harsh environments. Zinc is used sparingly by plants; hence, its accessibility at the nanoscale guarantees that the right quantities are delivered to the plant while preventing zinc poisoning soil and plants. During water stress conditions, nanoparticles help maintain plant-water interaction. Application of copper nanoparticles to the soil radically improves plant growth and yield while reducing wheat oxidative stress. When wheat plants are exposed to drought stress, the use of copper and zinc nanoparticles improves their antioxidant enzyme activity and relative moisture content while

lowering thiobarbituric acid levels, thereby reducing the effects of stress (Noman et al. 2020).

3.2.2 Biotic Stress

In addition to enhancing plant growth and vigor under various stress environments, nanoparticles have been identified as promising materials for the management of plant diseases and pests. Hence, through a variety of processes such as plant protection (nano pesticides), shock resistance, soil improvement, and crop development, these nanoparticles increase biomass production and agricultural output (Tortella et al. 2023). These nanoparticles suppress pathogens or increase disease defense by improving plant nutrients, reducing pathogen infestation such fungal, bacterial, and viral infections and consequently increasing nutrients, grade and crop production.

They primarily regulate plant antioxidative defense and natural phytohormones to influence the production of stress-related genes, which suppresses reactive oxygen species (ROS) inside the plant and promotes the development of the plant (Tripathi et al. 2022). There are many antibacterial processes used by metal nanoparticles for radical intervention on microorganisms. By internalizing and releasing ions, they can destroy cell membranes, DNA, and stop electron transport (Ndaba et al. 2020). Here, a few nanoparticle highlights that have been shown to be effective nanopesticides against a variety of phytopathogens, including *Alternaria alternata* and *Fusarium oxysporum*, are presented.

Inducing holes in the bacterial surface, releasing ions, and interacting with enzymes' disulfide or sulfhydryl groups, which disrupts metabolic activities, are a few of their methods of action (Munis et al. 2022). Silver nanoparticles have antibacterial properties in addition to promoting germination of seeds and altering the biochemical profile of *Silybum marianum* by boosting the amount of phenols, flavonoids, proteins, peroxidase function, and antioxidative enzyme activity overall (Salman Khan et al. 2016).

Copper nanoparticles are also effective nanopesticides and growth and nutrition promoters for plants. Prevalent phytopathogens such as *Fusarium oxysporum* are susceptible to their antibacterial effects. Foliar application of copper nanoparticles enhanced growth and chlorophyll content while decreasing *Fusarium* wilt incidence and severity by 68 and 66.5%, respectively (Lopez-Lima et al. 2021).

Additionally, titanium nanoparticles induce disease tolerance in wheat plants by stabilizing the plant's relative membrane stability index, water, phenolic and chlorophyll content as well as their antimicrobial activity against the bacteria *Bipolaris sorokiniana*, which causes spot mark disease in wheat crops (Irshad et al. 2020). Using zinc nanoparticles as a foliar spray on strawberries also resulted in a 43% decrease in *Botrytis cinerea* infections, a 28.5% increase in crop yield, and an 8-day delay in the spoiling of harvested fruits while being stored (Luksiene et al. 2020).

While nanoparticles offer positive impacts in agricultural production, particularly for stressed plants, several studies have examined their toxicity implications on human health and environments (Paramo et al. 2020; Javed et al. 2023). Nonetheless,

studies of dosages have just been conducted to identify the concentration and precise amount required to achieve good benefits without creating adverse reactions.

4 Conclusion and Recommendations

Marginal soils must be taken into consideration in order to increase crop production due to the growing global population and the requirement for sufficient food supply. Nanotechnology for smart agriculture has evolved as an intriguing prospective strategy to increase plant development under abiotic and biotic stress conditions in light of ongoing agricultural practices on marginal soils. Overall, administering nanoparticles can greatly enhance plant development and ensure adequate food supply. Of particular relevance on marginal lands is the application of micronutrient-based nanofertilizers. Such nanofertilizers have been shown to improve bio-availability of micronutrients, reduce soil fixation and absorption and improve dispersion and solubility, even under the harsh conditions imposed by marginal soils. Such micronutrient nanofertilizers include iron, zinc, copper, manganese, boron and molybdenum based products, amongst others.

Nanofertilizers in general have several associated benefits; the large surface area to volume ratio ensures that they are more available to plant roots than their macro counterparts. This not only enhances nutrient uptake but also contributes to minimising leaching and volatilization with concomitant enhancements in crop productivity. Furthermore, nutrient release from nanofertilizers is in a regulated manner in response to particular soil or plant requirements. Nanofertilizers are also beneficial in that the frequency and volume of fertilizer applications can be decreased by functionalizing some nanofertilizers with organic or inorganic coatings that can delay their release and improve their persistence in the soil. Moreover, nanofertilizers can be functionalized with other substances, such as insecticides, herbicides or growth regulators, which expand the repertoire of benefits associated with a single nanofertilizer product. A multi-functional product is of particular relevance in marginal lands that are prone to biotic and abiotic stresses.

Even though the application of nanomaterials in agriculture (Azam et al. 2022; Shalaby et al. 2022; Astaneh et al. 2021) has made significant strides, to confirm their prospective elongated benefits, numerous investigations are still required at the scale of hectares of agricultural fields and marginal lands for several years. The effect of prolonged nanofertilizer exposure on soil microorganisms needs to be further assessed. As several nanomaterials (nAg, ZnO NPs, TiO₂ NPs, nAu) are known and developed for their antibacterial properties (Wang et al. 2017). The soil ecosystem has a delicate balance and any effects which can cause an alteration in dominant bacterial species will in turn affect fungal communities and the final consumer. Therefore, long term studies are required to ensure that nanoparticles do not accumulate to toxic levels in agricultural soils over time affecting soil ecosystems, plant nutrition and inducing potential human health risk through ingestion.

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Role of Targeted Breeding to Improve Wheat Production on the Marginal Lands of Africa



A. Roopnarain, M. V. Kidson, B. Mndzebele, M. C. Hernandez-Soriano, and B. Ndaba

1 Introduction

Wheat is one of the main crops for food security in the world with an estimate production of 761 million tonnes (MT) globally (FAOSTAT 2022). Africa produces more than 25 MT of wheat on 10 Mha (FAOSTAT 2022). Sub-Saharan Africa (SSA) produced 7.5 MT on a total area of 2.9 Mha, accounting for approximately 30% and 1.4% of African and global wheat production, respectively (Tadesse et al. 2019; Assefa et al. 2021). Trend analysis of wheat production in SSA from 1970 to 2014 revealed a slight decrease of the total wheat production area. However, the total output increased from 2.8 to 7.5 MT due to an increase in wheat productivity from 1.3 t/ha in 1970 to 2.1 t/ha in 2014 (Tadesse et al. 2019). In descending order, the

A. Roopnarain (✉)

Microbiology and Environmental Biotechnology Research Group, Agricultural Research Council—Natural Resources and Engineering, Pretoria, South Africa

Department of Environmental Sciences, College of Agriculture and Environmental Sciences, University of South Africa—Florida Campus, Florida, South Africa

e-mail: RoopnarainA@arc.agric.za

M. V. Kidson

Microbiology and Environmental Biotechnology Research Group, Agricultural Research Council—Natural Resources and Engineering, Pretoria, South Africa

B. Mndzebele

Agricultural Research Council-Vegetable, Industrial and Medicinal Plants, Pretoria, South Africa

M. C. Hernandez-Soriano

Department of Biochemistry and Metabolism, John Innes Centre, Norwich, UK

B. Ndaba

Institute for Catalysis and Energy Solutions, College of Science, Engineering and Technology, University of South Africa—Florida Campus, Florida, South Africa

most important wheat producing countries in SSA are Ethiopia, South Africa, Sudan, Kenya, Tanzania, Nigeria, Zimbabwe and Zambia. Ethiopia has the most productive area (1.7 Mha), followed by South Africa (0.5 Mha) (Assefa et al. 2021; Yesuf et al. 2021).

Between 2011 and 2013, SSA countries bought 16.9 MT of wheat at a cost of USD 6 billion, thereby reducing the individual countries' fragile foreign currency reserves. Moreover, it is expected that the demand for wheat in developing countries will increase up to 60% by 2050 (Rosegrant and Agcaoili 2010). Wheat consumption in Africa is expected to reach 76.5 MT by 2025, with 48.3 MT imported. Meeting production demands for local consumption and minimizing imports require favorable environmental conditions such as temperature, water supply and soil fertility for optimal wheat cultivation and yield. However, increase in seasonal temperature caused by climate change are expected to diminish wheat yield globally, with an expected decrease of 20–30% in developing countries (Easterling et al. 2007; Rosegrant and Agcaoili 2010). Wheat yield is also expected to be challenged by stagnant or declining on-farm productivity, decreasing irrigation water resources, declining soil fertility, mono-cropping, and rising disease threats (Tadesse et al. 2019). Wheat cultivars resilient to predicted unfavorable climatic conditions and sub-optimal agricultural lands are required to ensure that adequate amounts of nutritional wheat is cultivated for the African population.

1.1 *Breeding Durum and Bread Wheat*

According to De Cillis (1927), the most widespread durum wheat landraces before 1925 were Rossia, Biancuccia, Sicilianu, Saragolla siciliana, Trigu arrubiu, Trigu biancu, Duro di Puglia, Realforte, Sammartinara, Russello, Scorzonera, and Trigu murru. The majority of these cultivars belonged to the *Mediterraneum* type (Monneveux 1991) and were characterized by high plant height (up to 180 cm) and lodging scores, as well as late anthesis. Following that, several landraces from the Near East and North Africa came into Italy, including some *Syriacum* kinds that were shorter and flowered earlier, (Monneveux 1991) such as Azizah and Eiti. Italy was the first country in the Mediterranean basin to start breeding 'conscious' durum wheat. The initial stage was to isolate the best pure lines from several landraces. It spread quickly, not just in Italy, where it occupied 60% of the total durum wheat-growing area, but also into other Mediterranean countries (e.g., Spain and Turkey), due to higher yields and superior quality compared to other cultivars available at the time (Dauno, Timilia, Russello, Triminia, Biancale) (Pecetti and Annicchiarico 1998). By 1950, Italian breeders were using intraspecific crosses, primarily *Mediterraneum syriacum* (Dib and Monneveux 1992; Bozzini 1970), to enhance durum, from which they selected earlier and shorter pure lines that were nevertheless prone to lodging (Capeiti, Patrizio, Casale, Castelporziano, Ichnusa, Maristella, Trinakria Appulo). Senatore Cappelli was widely employed in these crosses, as well as later ones, with this cultivar accounting for more than 80% of the cultivars

included in the Italian Register of durum wheat cultivars in 1987 (Mazzucotelli et al. 2020).

The gradual introduction of more productive cultivars with improved attributes occurred in tandem with advances in agriculture and management approaches. The introduction of the *Rht-1* dwarfing genes resulted in a substantial reduction of plant height and an increase in the harvest index for similar biomass levels, as a result of the synergy between breeding and management (Motzo and Giunta 2007). Through enhanced mechanization, the new semi-dwarf cultivars, shorter and more resistant to lodging, were also more efficient at utilizing and uptake of nitrogen. Semi-dwarf cultivars comprised 100% of the total area planted with durum wheat in the EU and high-income countries in 2014 (Lantican et al. 2005, 2016). Current cultivars are mainly challenged by environmental factors such as temperature and precipitation, as well as, soil factors (soil type, soil organic matter content), and nitrogen fertilizer input (Magallanes-López et al. 2017).

Bread wheat (*Triticum aestivum* L.) is the most widespread wheat crop providing a significant portion of the calorific daily diet in various parts of the world, up to 40–50% in Egypt and Turkey and 20% in the United Kingdom (Shewry and Hey 2015). Additionally, it is a relevant source of protein, fiber, B vitamins, minerals, and other phytochemicals in the human diet. Since the early domestication in the fertile crescent, wheat cultivation has spread worldwide reaching extreme latitudes such as 67°N in Norway, Finland, and Russia, and 45°S in Argentina, with the majority of crops grown in temperate regions and, to a lesser extent, sub-tropical and tropical habitats (Feldman 2001). In 2020 and 2021, global annual wheat production reached a record of 770 MT (FAO 2021), with China and India being the leading producing countries. Mankind has been captivated with the origin and evolution of wheat from ancient times. Once considered the sustenance of western civilizations, wheat has become one of humanity's most essential staple foods. Bread wheat is also the dominant wheat type that is cultivated in SSA (Tadesse et al. 2019).

1.2 Main Wheat Growing Environments in Sub-Saharan Africa

Though there are significant environmental differences between countries and across regions, the wheat producing area in SSA can be divided into two broad environments based on moisture availability, cropping techniques, and temperature regimes. During the summer season, the rain-fed production system predominates in the highlands of Eastern Africa (Ethiopia, Eritrea, Kenya, Uganda, Rwanda, Burundi, and Tanzania) and South Africa. During the dry winter season, irrigated systems are extensively used in the lowlands of Southern Africa (Zambia, Zimbabwe, Malawi, Madagascar, and Mozambique), Western Africa (Nigeria, Senegal, and Mali), and Sudan. Although the wheat growing environment in SSA can be divided into two broad mega-habitats (Tadesse et al. 2019), it is crucial to emphasize that

there is a great degree of diversity and environmental heterogeneity in each nation and at the regional level (Zimmerer et al. 2015).

Given the potential yields reported in Southern Africa's irrigated environments and Eastern Africa's optimum rainfall areas, there is still a significant opportunity to improve wheat production in these two regions if farmers use improved varieties and recommended integrated crop management practices. However, favorable policies and strong commitments from respective governments are required to establish infrastructure, attract investments, and enable market access. Current wheat technology promotion interventions in SSA, led by ICARDA and funded by the African Development Bank (AfDB), have demonstrated that it is possible to increase wheat production and productivity by utilizing improved varieties, recommended agronomic strategies, and involving all stakeholders along the wheat value chain (ICARDA 2016).

1.3 Marginal Lands in Africa

The term marginal land is commonly utilized synonymously with other concepts, namely areas which are unproductive, wasteful, underutilized, idle, abandoned or degraded (Dauber et al. 2012; Tógyer 2012). Generally, marginal lands are categorized into three types namely, land that is unsuitable for crop production, land with nutrient poor soils as well as land that is not economically efficient or beneficial (Shortall 2013). Reportedly, 36 percent of the global agricultural land (2.7 billion ha) is marginal (Csikós and Tóth 2023). The extent of the marginal land is estimated at 1.5 billion ha which is accounted to the one that is not suitable for agricultural production (Csikós and Tóth 2023). Typically, low-income countries often have nutrient depleted soils (Fischer et al. 2011). At the regional level, marginal lands constitute a significantly large proportion of currently cultivated lands in Asia and Africa. Hotspot areas were identified in South Asia (11 percent of land area) and SSA (nearly 27 percent of land area), especially Central and Eastern Africa (Eritrea, Mozambique, Central African Republic, the Democratic Republic of the Democratic Republic of the Congo, The Sudan, and large areas of Niger). Moreover, one percent of the total SSA area was identified as extremely marginal i.e. affected by five overlapping dimensions of marginality. These marginal lands are of high concern due to dramatic decrease in organic matter content, rapidly declining nitrogen levels, increase in soil acidity, depletion of micronutrients, expanding saline and arid areas and excessive phosphorus levels in certain cultivated soils (Scotney and Dijkhuis 1990). Nutrient depletion by crop uptake, as well as soil losses due to erosion largely explain some of these trends (Scotney and Dijkhuis 1990). Overall, land degradation is widespread and a growing concern due to the associated environmental impact.

Soil fertility is defined as the overall ability of soil to support vigorous crop growth by providing adequate supply of plant nutrients and suitable conditions for root establishment and growth. Therefore, soil fertility is a combination of chemical, physical and biological processes in soil, which are influenced by climate and

management factors (Carter 2020). The factors responsible for soil formation, particularly climate, parent material, and weathering give the soil mantle diverse characteristics (De Villiers et al. 2003). The results of soil formation are reflected in the properties of each soil body, such as organic matter content, texture and degree of leaching. This directly or indirectly influences soil fertility and it is now well established that soils respond differently to land management aimed at improving fertility.

Cultivation has had a negative impact on soil fertility since the first sod was turned, particularly through the degradation and rapid loss of organic matter. Allison (1973) already stated that nitrogen is the most essential ingredient in soil organic matter from an economic standpoint. Similarly, Scotney and Dijkhuis (1990) highlighted that all fertile soils must be enriched in adequate (3 to 6%) amount of organic matter. There is evidence that extensive tillage-based cultivation occurs at a fast growing rate in Southern Africa (Le Roux 2014). Continuous tillage-based agriculture has caused negative physical alterations in many soils particularly compaction in light-textured soils.

According to du Plessis (1986), sediment transport by erosion contributes significantly to fluctuations in soil fertility and is prevalent throughout South Africa. Particularly, wind and water erosion can cause substantial soil losses (Eswaran et al. 2019). When undisturbed soil is turned for agricultural use, carbon mineralization rapidly increases and aggregation and carbon storage capacity severely decrease (Hernandez-Soriano et al. 2018), increasing the vulnerability of soil to erosion. Eroded material is always richer in nutrients than the soil left behind (Allison 1973) since essential nutrients contained in organic matter are lost with soil erosion (Lal et al. 2004). Nutrient losses and imbalances are mitigated by application of fertilizer and liming material. Although these strategies have improved the inherent nutritional content of agricultural soils, unsustainable management of soil and disregard for the relevance of soil as a limited resource has resulted in significant over- and under-fertilization. Mulching is a popular conservation tillage strategy key in conservation agriculture and has been promoted widely in SSA to buffer smallholder farmers against the adverse effects of soil fertility decline to stabilize crop yields (Yuan et al. 2022). The benefits of mulching, particularly on sandy soil, were already reported by Scotney and Dijkhuis (1990).

Overall, it is essential to highlight that the production of wheat in SSA is primarily spread in East and Southern Africa, where wheat is often cultivated in marginal areas despite the inherent management challenges (Di Mola et al. 2021). Production in these areas substantially contributes to global production. However, with the rise in population and associated food demands it is crucial to broaden wheat cultivation to marginal lands throughout Africa to ensure that wheat importation is minimized and sufficient wheat is grown for the local population. Thus, there is a requirement to cultivate wheat under sub-optimal conditions with minimal amendments whilst maintaining yield and retaining its nutritional value. Both bread and durum wheat production may be optimized on marginal lands through strategies such as targeted breeding and biotechnology. This chapter aims at revealing the biotic and abiotic constraints challenging wheat cultivation on marginal lands with the intention of outlining breeding strategies and both above- and below-ground targeted traits that may aid in improving resilience of wheat cultivars on sub-optimal agricultural lands.

2 Wheat Cultivation Constraints on Marginal Lands

Numerous abiotic and biotic stresses threaten wheat production globally (Afzal et al. 2015). Plants utilize acquired and induced systemic resistance to tackle these stresses, but in extreme scenarios such as those experienced on marginal lands, these strategies are insufficient, and compromise crop growth. In addition to light-weight and shriveled kernels due to stunted growth, the harsh weather conditions may also result in seedborne illnesses. These illnesses may be due to inadequate distribution of the seed in comparison to the pathogen's population density on weed species or in soil, leading to the seed being the cause of disease transmission at high temperatures, which further reduces crop productivity (Von Cossel et al. 2019). To address the numerous challenges related to biotic and abiotic stresses, a variety of crop cultivation strategies have been developed. Quantitative trait loci (QTL) can be used to map inherited genes for beneficial traits such as moisture tolerance. The identification of QTLs provides functional molecular markers that are associated with the desired genetic region. Quantitative mapping can therefore be applied to improve wheat through molecular aided selection, accelerated fine mapping and map-based gene cloning. Extensive research is dedicated to introduce drought resistance genes into the wheat genome using such techniques (Tuberosa and Salvi 2006). To reduce the effects of waterlogging and micronutrient deficiency stress, other genetic engineering methods are also being investigated (Von Cossel et al. 2019).

The increased severity of biotic stresses such as pest and diseases as well as abiotic stresses including drought and heat on the wheat agri-food chain (Fig. 1), will directly result in low grain supply and therefore compromise food security (Dhakal

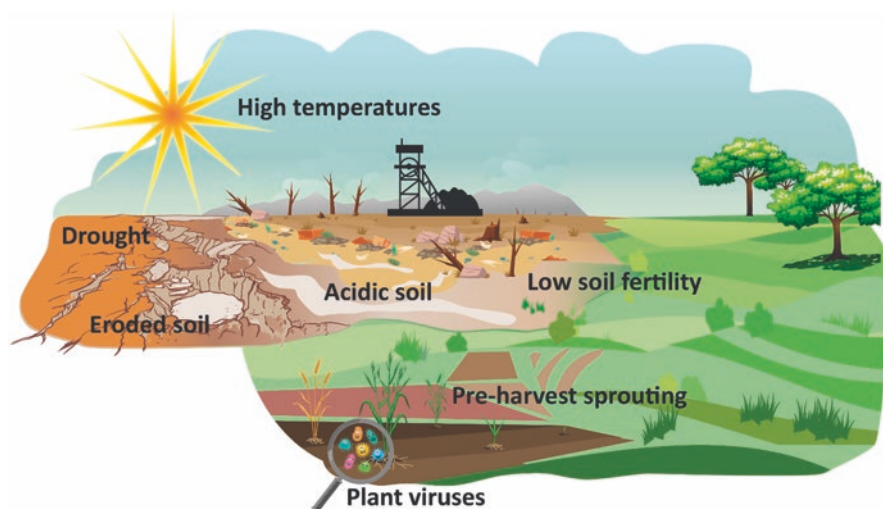


Fig. 1 Major abiotic and biotic stresses experienced by wheat on marginal land

et al. 2021). It is anticipated that the yield of wheat in developing nations would decrease by 20–30% due to increased temperatures associated with climate change (Nelson et al. 2010). According to current estimates, for every 1 °C temperature increase, the world's wheat yield can decline up to 6% (Asseng et al. 2019).

Reduced or stagnant productivity, decreasing supply of water for irrigation, loss of soil fertility, and vulnerabilities to newly developed diseases have a detrimental effect on wheat yield on marginal lands. A recent example was the dramatic impact of Ug99 stem rust in East Africa and temperature-tolerant yellow rust races (Solh et al. 2012). The abiotic and biotic pressures that wheat faces on marginal lands is the focus of this section.

2.1 Abiotic Stresses

Heat and drought stress, erosion, pre-harvest sprouting, poor soil fertility, soil acidity and waterlogging are the most common abiotic challenges in marginal soils. East African countries such as Ethiopia, Kenya, Tanzania, Uganda, and Southern parts of Africa e.g. South Africa, Malawi and Zambia are particularly vulnerable to these restrictions. Interestingly, these are the regions where wheat is primarily cultivated in SSA. Drought stress significantly alters the physiological, biochemical and molecular wheat properties. Drought regularly affects more than 50% of wheat-producing land, which can cause a decrease in production of approximately 10% (Grote et al. 2021). For wheat improvement initiatives on marginal lands, it is essential to understand how these pressures affect the crop. All developmental stages are negatively impacted by drought stress and local climate (Dube et al. 2020). A decrease in seed weight, protein content, and chlorophyll content are also affected by drought due to an increase in proline levels (Grote et al. 2021).

Due to shorter seasons, developmental stages times are reduced, resulting in a decrease in biomass, early leaf development, and negative morphological and biochemical alterations. Also, high temperatures during wheat reproductive stages significantly reduce grain quality and yield (Jha et al. 2014). High temperatures, as reported by Grote et al. (2021) and Asseng et al. (2017), alter the photosynthetic process, which has a detrimental impact on wheat growth and yield. Wang et al. (2018) found wheat chloroplast and thylakoid lamellae to have ultrastructure degradation due to heat stress. Khan et al. (2013), stated that heat stress in wheat plants reduced the activity of RuBisCo, photosynthetic nitrogen use efficiency (NUE), as well as net photosynthesis. According to other reports, high temperatures also inhibit photosystem II, thereby hindering wheat's photosynthetic system (Djanaguiraman et al. 2018).

Conversely, extreme low temperatures increase wheat sterility circa 98% (Chakrabarti et al. 2011). During early-stage development of grain and flowering, frost damage reduces the kernel number per spike. Frost events results in the development of a thinner band in the spikes, the awns grow curled, and the spikes are nearly erect at maturity due to lower grain weight. It has been reported that low

temperatures at the anthesis stage enhance sterility of pollen in both *aestivum* and durum wheat, restricting pollen grain germination. Freezing temperatures can cause substantial damage to wheat during its reproductive period, greatly reducing yield of grain (Xu et al. 2022).

Grote et al. (2021) estimate that over the last 50 years, two-thirds of the agricultural land has been degraded in Africa and Asia. The loss of agricultural land is currently expected to rise up to 12 million hectares a year, and this will potentially result in grain losses of approximately 20 MT annually. Soil erosion and associated infertility due to nutrient impoverishment and poor water retention capacity, desertification, salinization and acidification are some of the detrimental impacts of land degradation on agricultural production, which increasingly relies on costly, unsustainable application of fertilizers and other synthetic amendments.

2.2 Biotic Stresses

Biotic stresses such as fungal infections, weed and insect pests have a negative impact on wheat quality and yield (Beres et al. 2020). These challenges are particularly severe in SSA. Major wheat diseases that are widespread in the East African countries such as Ethiopia, Kenya, Uganda and Tanzania, include tan spot (*Pyrenophora tritici-repentis*), rusts (*Puccinia* spp.), and fusarium head blight (*Fusarium* spp.). A range of pests and diseases linked to environmental changes associated with climate change are expected to rise, as reported by the epidemics of yellow and stem rust strains in West and Central Asia as well as selected Northern parts of Africa (Solh et al. 2012; Beres et al. 2020).

Rust causes up to 100% yield losses in the Ethiopian highlands, which highlights the failure of popular wheat varieties like the semi-dwarf wheat variety (Ayele et al. 2008). Warmer climates at low and mid-altitudes are more prone to stem rust due to *Puccinia graminis* f. sp. infestations (Badebo and Hundie 2016). In several SSA nations, weeds, primarily grass weeds, also significantly reduce wheat yield (Tadesse et al. 2019), due to competition for nutrients between wheat and weeds.

The most common weed reported in wheat cropping system is *Phalaris minor* Retz. (Tshewang et al. 2018). The growth and spread of this weed is usually prevented by increasing wheat seeding rate to reduce the space available for weed growth. In other instances, several broadleaf weeds are reduced by manual weeding. Currently, diverse strategies such as drone sensing and nanotechnologies are available for efficient weed removal (Esposito et al. 2021) although further research is required.

Several species of aphids can also damage wheat and reduce yield, including *Metopolophium dirhodum*, *Rhopalosiphum padi*, *Diuraphis noxia* among others. Abiotic stresses such as elevated temperatures exacerbate the growth of aphids and the associated wheat damage (Kamran et al. 2013).

Overall, wheat production on marginal lands faces both constraints and opportunities. The key to maintaining and further improving wheat yield on marginal lands

strongly depends on the availability of appropriate resistant cultivars with desirable physiological features. Managing soil fertility is another crucial aspect that will impact not just the sustainability of wheat production but also that of other main crops. Developing strategies for wheat breeding might help advance and support the utilization of marginal lands for wheat growing in the right direction.

3 Strategies for Wheat Breeding

Recent advances in breeding methodologies and wheat genetics are powerful resources to introduce beneficial traits in wheat crops. Key milestones have been the development of quantitative trait mapping and CRISPR-based genome modification as well as the provision of an annotated reference wheat genome (IWGSC et al. 2018).

Since the domestication of the first grain crops, plant breeders have developed a number of innovative technologies to apply in their quest for crop line improvements. These include second and third generation sequencing platforms, which means that breeders can afford to use DNA markers to assist in selections and facilitated gene discovery. A major discovery by botanists was that plants can be grown for 24 h using artificial light. A partnership with NASA and Utah University, developed the “USU-Apogee”, a dwarf wheat line for rapid cycling. Innovation in phenotyping of field-grown crops can only be combined with speed breeding for traits that are stable between the target environment and conditions used in speed breeding, such as long day lengths (Hickey et al. 2019). An extension of speed breeding is the gene editing using CRISPR, where the sgRNA directs the Cas9 enzyme to the target DNA site, and cuts the DNA. This will allow genome editing using CRISPR-Cas9 ribonucleoprotein complexes, for a number of species including wheat (Hickey et al. 2019).

While high yield, pest resistance wheat cultivars are now widely available in many countries, there is an increasing interest in the introduction of traits linked to plant resilience to abiotic and biotic stresses and the modulation of key soil microbiome functions such as nutrient cycling. Root phenotyping for traits related to crop performance or ecosystem services has been a focus in root biology since the 70's. During the ISRR2/Rooting2011 symposium the need for phenotyping root traits for changing environmental conditions, including the root-microbial interactions was highlighted (Kawasaki et al. 2021). For instance, tuning the nitrogen metabolic pathways in soil can help minimize fertilizer inputs without compromising yield goals. To achieve these goals, wheat breeding will need to expand the mining for new traits to incorporate relevant root capabilities to tune soil microbial communities and their functions to exploit the potential benefits of this interaction (Carley et al. 2022; Liu et al. 2020).

3.1 *Stresses on Marginal Soils*

South Africa's average rainfall is 464 mm per annum, which is about half of the global average of 990 mm per annum (www.Britanica.com). Approximately 80% of the land area is classified as arid to semiarid (ARC 2004) and therefore local farmers are challenged by low rainfall, e.g., about 400 mm p.a. in the eastern Free State. Moreover, rain events usually occur as short intense thundershowers (ARC 2004; Laker 2021). However, the soils that would normally be classified as marginal due to the climatic conditions, can be used for crop cultivation because of the soil texture. The sandy nature of the soil allows for rapid infiltration of most of the rainfall accumulating on the subsoil impenetrable layer (plinthic horizon), thus providing a source of water for the crop between rainfall events (Laker 2021).

Soil erosion is a natural process, but current rates of erosion due to humankind activities are unsustainable. In South Africa, soil erosion is estimated to reach 13 tons of top soil/ha/yr, while the rate of soil formation is about 5 ton/ha/yr (Le Roux 2014). Certain soils such as the duplex soils and the windblown soils in the Free State province, are particularly prone to erosion. The loss of topsoil is a direct loss of soil fertility, challenging seed germination. In an effort to boost crop cultivation and simplify the recommendations in the Transkei, a blanket rule was put into place that recommended that a slope of 12% or less could be cultivated but in certain areas large scale erosion took place. In a study conducted in Transkei, D'Huyvetter (1985) found that each soil needs to be considered separately as erodibility varies between soil types.

To boost production, certain crops are artificially irrigated. This has resulted in an increase of soil salinity due to the salt content in the irrigation water. It is estimated that globally 50% of the irrigated soils have elevated levels of salinity (Shabala and Pottosin 2014). Salinity has led to large annual losses of soil, which is further aggravated by the conversion of agricultural land into other uses such as urbanization. Salinity results, for instance, in a reduction in cellular potassium (K) in the roots and shoots. Furthermore, it has been reported that there is a strong positive correlation between shoot K content and plant salinity tolerance (Garthwaite et al. 2005). Salinity has three associated effects (1) reduced water availability due to high salt concentration resulting in osmotic imbalance; (2) sodium toxicity to the cell metabolism and (3) oxidative stress damage resulting in increased ROS production. The negative effects of each of the factors can be mitigated by the addition of K (Cakmak 2005). Intercellular K homeostasis is a prerequisite for optimal growth. With biotic and abiotic stresses, there is a disturbance in the intracellular K homeostasis. Plants' tolerance to drought is related to its ability to maintain the K concentration in the cells. Maintaining adequate cellular K concentration is vital in the adaption to drought by overcoming the osmotic potential of the soil, which can decrease with increasing salinity (Umar et al. 2011). Potassium transport systems are also important for virus recognition. Shabala and Pottosin (2014) showed there was a change in K fluxes within 10 min of infecting a plant with viruses, which aided the virus recognition and aided the plant defenses.

Globally only about 50% of the N-fertilizer applied to the soil is utilized by the crop. The rest is lost through volatilization and lixiviation. Therefore, the introduction of traits that can increase nitrogen use efficiency (NUE) is being a main target for breeding programs. Nitrogen Use Efficiency can be defined as the grain dry matter yield (kgDM ha^{-1}) divided by the supply of available nitrogen (N) from the soil and fertilizer (kgN ha^{-1}) (Moll et al. 1982). Methods proposed to improve NUE include decreasing the rate of soil bacterial oxidation of ammonia or urea (Dargie et al. 2020) or delayed leaf senescence. This trait for the leaf to remain green longer is referred to as the ‘stay green’ phenotype (Thomas and Smart 1993). By delaying senescence, more carbohydrates are provisioned for above ground growth and the roots for prolonged nitrogen uptake. Root morphological traits that can promote nitrogen can also contribute to increase NUE (King et al. 2003).

3.2 *Potential of Landraces for Wheat Improvement*

The term “landrace” has generally been defined as a cultivated, genetically heterogeneous variety that has evolved in a certain eco-geographical area and is therefore adapted to the edaphic and climatic conditions and to its traditional management and uses (Casañas et al. 2017). In the dawn of wheat domestication (about 10,000 years ago), farmers selected various traits such as plant height, number of spikes and weight of spikes and grain, contributing to improved yields (Peng et al. 2011). The selection process led to a large number of unique genotypes suited to specific ecological niches. The selection of traits included growth rate, phenology, cold, salinity, drought and biotic stress tolerance (Masood et al. 2005).

Generally, landraces have a lower yield potential but carry wider genetic resources due to their unique natural and human-driven selection. As they are well adapted to local stresses that dominate in the area of crop production, they have a greater yield stability (Zeven 2000). Farmers can reduce the risk of crop failure by maintaining a variety of wheat landraces (Zeven 2000). The utilization of landraces by direct crossing is a reasonably straightforward and attractive option (Reynolds et al. 2007). This is due to the closer affinity with modern cultivars than wild species, hence landraces are a key underpinning material in breeding programs (Newton et al. 2011).

With the introduction of new pests, landraces are collected from the place of the pest’s origin. For instance, two Iranian wheat landraces were used as donors of Russian wheat aphid resistance in a South African breeding program (Du Toit 1989). The origin of the aphid pest was West Asia and Middle East (Puterka et al. 1993). In 1978, it moved to South Africa, where sources of wheat resistance to the aphid were sought.

Of the various biotic stresses affecting wheat production, rust diseases are the most severe. Black and yellow rusts have devastating impacts, resulting in up to 50% yield loss. Long-distance wind dispersal, large scale production and the aphid ability to mutate into highly aggressive pathotypes among other factors can further

aggravate the impact of this pest (Bhardwaj et al. 2019). A group of landraces have been reported to resist yellow rust (Long et al. 2019) as well as brown and black rusts. Leaf rust-resistant cultivar Americano 44d was introduced in Uruguay during 1918, and has shown long-lasting resistance associated to two resistance genes (Roelfs 1988). Another relevant example of pest resistance is the presence of powdery mildew resistance genes currently reported for more than 100 landraces (McIntosh et al. 2017).

Abiotic stress management is a key factor in wheat cultivation that include water stress (drought, flooding), temperature, salinity, mineral deficiencies, metal toxicity and UV radiation. Abiotic stresses are becoming increasingly prevalent and extreme with climate change, particularly in marginal lands. Abiotic stresses are strong effectors on yield and quality reduction (Landi et al. 2017). The most cost-efficient approaches to tackle abiotic stress is to breed cultivars to introduce traits that increase plant tolerance to stress. Selected Iranian and Chinese landraces have demonstrated large phenotypic variation for drought tolerance (Lin et al. 2019), while several Mexican landraces exhibit tolerance for temperature and drought tolerance (Hede et al. 1999).

Bread wheat landraces that are reported to have a salt exclusion mechanism regulated by the *Nax* gene have been obtained through breeding in the Middle East, a naturally saline area (Munns 2005). Landraces from Nepal, Pakistan and Iran have shown significantly higher yield under a wide range of salt concentrations in soil. Madeiran wheat landraces have been reported to exhibit a substantial tolerance to aluminum toxicity (dos Santos et al. 2005). Quantitative trait loci for P-deficient tolerant cultivars have been reported for Chinese wheat landraces (Lin et al. 2020). Mineral deficiencies are a critical challenge which results in impaired growth and development. Phosphorous is generally abundant in soil but frequently as species not available for plant uptake, which results in high demands for artificial P application.

There is an increasing awareness among consumers of the importance of a healthy, diet, which has led to an increased consumption of whole wheat. Whole wheat-based foods are reported to reduce chances of type II diabetes, cancer, obesity etc. (Boukid et al. 2018). Traditionally, increasing yield was the main focus of breeders but this is shifting due to changes in consumers demands. Historic cultivars are reported to provide higher content of essential micronutrients including Cu, Fe, Mg Mn, P, Se and Zn, than modern cultivars (Nsarellah et al. 2011).

3.3 Breaking Yield Barriers Through Breeding

Since the rise and domestication of bread wheat, (*T. aestivum*) approximately 8000 years ago, wheat has been the staple food crop for the major civilizations of Europe, West Asia and North Africa (Rauf et al. 2015). World wheat production increased by 3.3% between 1949 and 1978 during the ‘Green Revolution’ (Hawkesford et al. 2013). High wheat yields can be attributed to genetic improvement and extensive

artificial irrigation, application of pesticides and fertilizers (Rauf et al. 2010). However, expected increments in yield diminished to 1.5% per year between 1981 and 1990. Currently, global market demands require between 3 to 4% yield increase per year. Improving yield potential. i.e., “the yield of a cultivar when grown in environments to which it is adapted, with non-limiting nutrients and water, and with pests, diseases and weeds effectively controlled” (Evans and Fischer 1999) can be achieved through:

- Increasing spike fertility—the final grain production is affected by the yield components (spikes m^{-2} , number of grains spike $^{-1}$, and thousand grains weight). The number of grains can be increased by enhancing the number of spikelets per spike and the number of grains per spike.
- Altering sinks that compete with spike fertility—This has been done by reducing the biomass to the semi-dwarf varieties, thus reducing the excessive vegetative growth such as non-productive tillers.
- Increasing photosynthetic capacity—Photosynthetic rate is tightly associated to the amount of Rubisco. Rubisco catalyses the assimilation of CO_2 by the carboxylation of RuBP in the Calvin Cycle and oxygenation of RuBP that initiates the process of photorespiration. Therefore, increasing Rubisco expression would increase the photosynthetic rate (Long et al. 2019).
- Improving biomass and radiation use efficiency—A way of increasing biomass at anthesis, and thus making more assimilates available to increase spike biomass, is to enhance pre-anthesis radiation-use efficiency.
- Weed competition—Wheat, compared to other cereals, is a poor competitor to weeds. Worldwide wheat loss due to weeds is around 23%, compared to 16% for fungi and bacteria. Promoting early development on wheat can contribute to out-compete weeds (Bond and Grundy 2001). Allelopathy is another potential important weed suppression trait. Some wheat varieties have shown to inhibit the growth of weed species (Wu et al. 2000).
- Resistance to fungal diseases—Three major rust diseases continue to cause major losses in various parts of the world, hence receive a lot of attention in breeding programs. These are stem or black rust (*Puccinia graminis*), leaf or brown rust (*P. tritricina*) and stripe or yellow rust (*P. striiformis*). As a result, breeding to resist rust is an ongoing strategy. Breeders are looking for alternative approaches to resistance management such as the slow rusting development by Van der Plank in 1963 and refined for leaf rust (Caldwell 1968).

3.4 Methods of Plant Breeding in South Africa

Breeding programs for wheat face many challenges in South Africa. The Stellenbosch University – Plant Breeding Laboratory (SU-PBL) was established to meet the requirements of the wheat industry. It is situated at the Welgevallen Experimental

Farm and forms part of the research program of the Stellenbosch University Department of Genetics in the Faculty of AgriSciences.

The wheat breeding program includes various components: (1) The SU – PBL initiates pre-breeding for the introduction of existence and/or novel genes and/or beneficial traits into breeding programs. The product is released to plant breeding companies to conduct selections. The beneficiaries of the work who carry out further research would be ARC – SGI, SENSAKO and PANNAR; (2) Stakeholder engagement—a crucial component which can include funders such as GrainSA, Department of Science and Technology and Winter Cereal Trust (WCT); and breeding programs including ARC – SG (public), SENSAKO and PANNAR (private). (3) Germplasm gathering and screening which include field-based trials of germplasm gathered from international collaborators and self-developed at several trial sites across the production area; (4) MS- MARS crossing program—the pre-breeding is based on the male sterility mediated marker assistance recurrent selection scheme (MS_MARS). (5) Molecular marker identification—The acquired germplasm is screened markers that can include disease resistance genes (rust, powdery mildew and fusarium), quality genes (glutenin), agronomic traits (height), and related markers (thousand grain weight). (6) High throughput phenotyping—Drones are being used to facilitate automated phenotyping, along with RGB and NDVI maps. (7) Capacity building is an essential component to build and develop the breeding industry.

For farmers and scientists to achieve the goal of meeting food requirements by 2050, wheat breeding will have to increase the yield, while improving the nutritional value of the grain under adverse biotic and abiotic conditions. Moreover, when extending wheat cultivation to marginal lands, relevant traits are required to be bred into wheat without compromising yield and quality.

4 Targeted Traits for Wheat Cultivation on Marginal Lands

Marginal lands are characterized by crucial factors such as the heterogeneity and topography of soils as well as erratic climatic conditions and pest outbreaks, which challenges cultivation of food crops. Therefore, farmers that utilize marginal lands for crop cultivation require a diversity of products i.e. crop varieties with the capability to withstand the multitude of adverse conditions imposed. Such varieties are expected to thrive in low fertility soils and erratic weather conditions with minimal inputs, whilst producing adequate yield to warrant cultivation (Bellon 2007). The urgent need for targeted crop traits beyond yield alone for marginal land wheat cultivation is an outstanding research call. Such traits include both above- and below-ground traits that facilitate tolerance to the adverse conditions imposed by the marginal land of interest (Table 1).

Crossovers as well as spillovers have contributed to wheat cultivation on marginal lands. A crossover refers to the cultivation of the same variety of wheat on both marginal and favorable land whereas a spillover is a bred variety that is

Table 1 Promising above- and below-ground phenotypic traits and associated adaptation strategies for grain crops to withstand harsh environmental conditions on marginal lands (Adapted from Renzi et al. 2022)

Threat	Goal	Adaptation strategy	Phenotypic trait	Target environment
<i>Below-ground traits</i>				
Weeds	Minimize negative impact of weeds	Outcompete weeds	• Low dormancy of seeds • More widely spread root systems	Transient stress
Excessively cold temperatures	Survival during winter	Resilience under cold temperatures	• Survival testing for seeds under extreme cold	Very cold winters
Drought	Escape from drought	Complete life cycle prior to water deficit	• Rapid germination and elevated rate of growth	End-of-season drought
Drought and elevated temperature	Tolerate drought and high temperature conditions	Adaptation to deficit in water	• Deep rooting system • Elevated root:shoot ratio	Terminal and transient drought
Drought	Tolerate drought	Maximize uptake of water and reduce depletion of soil water	• Increase in root:shoot ratio	Transient drought
Unfavorable conditions imposed by biotic stresses, predation and grazing	Tolerate unfavorable conditions	Improved resilience	• Elevated seed dormancy • Elevate growth rate of seedlings • Hypogeal emergence • Deep rooting • Elevated allocation to storage organs and roots	Transient stress
<i>Above-ground traits</i>				
Weeds	Minimize negative impact of weeds	Outcompete weeds	• Elevated plant height • Elevated plant growth rates • More tillers per plant • Denser leaf canopies • Elevated specific leaf area • Elevated dry matter	Transient stress

(continued)

Table 1 (continued)

Threat	Goal	Adaptation strategy	Phenotypic trait	Target environment
Excessively cold temperatures	Survival during winter	Resilience under cold temperatures	• Survival testing of above ground parts under extreme cold • Ability to regrow after freezing • Glume hairiness/pubescence	Very cold winters
Drought	Escape from drought	Complete life cycle prior to water deficit	• Larger seed size • Remobilization of dry matter and elevated harvest index • Earlier flowering and physiological maturity • Elevated specific leaf area	End-of-season drought
Drought and elevated temperature	Tolerate drought and high temperature conditions	Adaptation to deficit in water	• Increased thickness of leaf cuticle • Elevated leaf wax production • Smaller and thicker leaves • More green photosynthetic organs • Increased reflectance of leaves or steep angle orientation • Low specific leaf area • Foliar nyctinasty thereby optimizing the capture of sunlight	Terminal and transient drought

(continued)

Table 1 (continued)

Threat	Goal	Adaptation strategy	Phenotypic trait	Target environment
Drought	Tolerate drought	Maximize uptake of water and reduce depletion of soil water	• Lengthening period for seed filling • Reduction in leaf area • Ability to adjust phenology in response to rainfall events • Increased leaf thickness • Delay in leaf senescence • Canopy temperature reduction • Movement of leaf	Transient drought
Unfavorable conditions imposed by biotic stresses, predation and grazing	Tolerate unfavorable conditions	Improved resilience	• Plasticity of phenology to extend the growing season • Production of secondary shoots • Low reproductive effort • Indeterminate growth	Transient stress

developed from established varieties meant for favorable lands (Lantican et al. 2002). Crossovers may not always be ideal on marginal lands as cultivars bred for similar, favorable conditions may not thrive under the heterogeneous landscape provided in marginal lands. Marginal lands may be more conducive to the cultivation of landraces i.e. traditional varieties that lack commercial crop improvement, that are genetically diverse, locally adaptable and are often associated with traditional farming (Villa et al. 2005). The natural ability of landraces to adapt to unfavorable farming conditions makes them potentially suitable to ensure yield stability and tolerance to biotic and abiotic stresses that are evidenced on marginal lands (Colombo et al. 2022). The identification of the traits in landraces that contribute to their resilience on marginal lands may aid in developing varieties that integrate resilient traits with the higher yield of modern varieties that may be more suitable for economical marginal land wheat cultivation (Adhikari et al. 2022). Such above- and below-ground phenotypic (anatomical, phenological and morphological) traits are outlined in Table 1. Such traits may act as a guide for breeders in search of new promising germplasms.

Unlike crop production under favorable conditions, the dominant criteria when selecting a cultivar for marginal lands is not necessarily seed yield. Indeed, such

cultivars are required to possess adaptive traits that enable them to tolerate and thrive under adverse conditions such as heat, drought, low fertility, extremes in pH, salinity, as well as several biotic factors (Redden 2013). For example, the selection of taller and late-cycle wheat varieties is favored on the marginal lands of Patagonia. Tall crops are preferable as they compete with weeds and late-season genotypes are beneficial as they contribute to prolonged periods of root growth which enables the use of nutrients and water that is available deeper in the soil (Richards 2006). Different wheat cultivars possess varying beneficial traits, which impact differently on marginal lands and may even contribute to improving the quality of the land in the long term. For example, cultivars with firmer stubble that are retained as post-harvest residues would aid in elevated moisture retention in the soils and minimize erosion (Silenzi et al. 2012). Perennial wheat cultivation was also shown to improve microbial activity and biomass as well as soil organic carbon on marginal lands in comparison to annual wheat (Audu et al. 2022).

5 Conclusion and Recommendations

Sustainable wheat cultivation has a key role for current and future food security. Wheat is now cultivated globally and has risen to the highest level of important food sources in the world. Whilst overall wheat productivity has increased over the decades in SSA due to the modernization of farming systems, future challenges are expected due to climate change, stagnant or declining on-farm productivity, decreasing irrigation water resources, declining soil fertility, mono-cropping, and rising disease risks. Moreover, the available arable lands are diminishing because of erosion, pollution and several other factors related to the adoption of unsustainable farming practices that mainly focus on yield optimization.

This has drawn attention to the world's marginal lands for potential agricultural intensification to support the nutritional requirements of the growing population. Marginal lands are characterized by poor soil quality and are ravaged by biotic and abiotic stressors. Hence, wheat cultivars that are selected for cultivation on such lands are required to be highly resilient. When selecting such cultivars, it is essential to prioritize adaptive traits that provide tolerance to the adverse conditions imposed by marginal lands as well as sufficient yield to ensure economic viability. Whilst crossovers of wheat varieties have potential to improve wheat yield on sub-optimal agricultural lands, targeted breeding i.e. spillovers is proposed as a better option to substantially augment the wheat gains on marginal lands. Targeting specific traits that are relevant to the conditions imposed on the marginal land of interest will result in increased tolerance of the crops to adverse conditions and more stable yields. For example, on marginal lands that experience end of season drought, it is suggested that the selected cultivars are bred with the phenotypic trait of rapid germination and elevated growth rate to ensure that the life cycle of the crop is complete prior to the onset of drought.

In the current and future agricultural panorama, landraces require adequate consideration in breeding strategies. Landraces offer substantial benefits when considering wheat cultivars for cultivation on marginal lands. They may be utilized as donors for the improvement of specific traits or as recipients for the improvement of potential yields of the landraces themselves (Adhikari et al. 2022). It is therefore imperative to monitor the genetic diversity harbored in landraces and to intensify their genetic and phenotypic characterization to find beneficial alleles of interest that may be utilized in breeding programs (Lopes et al. 2015).

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Enhancing Above and Below-Soil Arthropods to Improve Production on Marginal Lands



M. M. Makwela and M. E. Malobane

1 Introduction

Given the increasing need for food, feed, and bioenergy, as well as competing land claims, environmental degradation, and biodiversity loss, the use of marginal agricultural land for crop production is becoming an enticing alternative (Muscat et al. 2022). As a result, rehabilitating marginal land is crucial for extending the production area as well as maintaining sustainable agriculture. Although flood-prone soils, salty and acidic soils, polluted soils, degraded soils, drought-affected soils, and nutrient-deficient soils are typical of marginal lands, they will contribute to the challenges of land scarcity and economic pressure (Kang et al. 2013). Therefore, improving and restoring marginal land for production purposes necessitates several steps, including considering agricultural management practices that promote biodiversity and related ecosystem services (Gibbs and Salmon 2015; Merckx and Pereira 2015).

Soil biodiversity determine the interplay of chemical, physical, and biological properties of soil (Massaccesi et al. 2020). To maintain biological soil fertility and to ensure the proper cycling of nutrients, the soil ecosystem relies on its faunal inhabitants. Arthropods that live underground are an integral part of the soil arthropod community (Jowett et al. 2021). These organisms make up more than 80% of the edaphic fauna, accounting for a significant portion of both the meso-fauna (below) and macrofauna (above) (Chamorro-martínez 2022). This arthropod

M. M. Makwela

University of KwaZulu-Natal, College of Agriculture, Engineering, and Science, School of Life Science, Scottsville, South Africa

M. E. Malobane (✉)

University of South Africa, Department of Agriculture and Animal Health, Florida, South Africa

e-mail: malobme@unisa.ac.za

performs vital ecological roles, such as decomposing plant litter, ecosystem engineering and biological pest control (Gongalsky 2021; Zulu et al. 2022). Most edaphic arthropods are generalist predators that regulate crop pests and weed seeds, while other edaphic species supply nutrients for cycling, building, and controlling soil organic matter (SOM) (Bhriain et al. 2002).

The concept of promoting marginal land has evolved to meet numerous management goals, including environmental protection, conservation of ecosystem service, and long-term sustainability (Kang et al. 2013). Improving ecosystem functions of marginal lands (Pearce and Venier 2006; Asfaw and Zewudie 2021) depends on biological productivity, soil fertility, and carbon sequestration, pivotal functions provided by soil arthropods (Plieninger and Gaertner 2011; Muscat et al. 2022). Furthermore, the conservation and rehabilitation potential of degraded lands linked with soil biodiversity is under-researched. This article provides a synopsis of the literature on the importance of above and below-soil arthropods for increasing the productivity of marginal lands. It answers the crucial question of whether soil arthropods can contribute to marginal land production and which production practices can promote their functional role.

2 Soil Biodiversity and Ecosystem Function on Marginal Land

Soil fauna and their biodiversity are the driving force behind most soil processes. Their ecosystem functions drive the multifunctionality of soil systems (Ponge et al. 2013). Within the soil food web, below and above soil arthropods play a predominant role in process of shredding, transforming, and decomposing soil organic matter (Diekötter et al. 2010). Soil organisms drive nutrient cycling, including N fixation, plant nutrient and water uptake, plant productivity (Andersen et al. 2002; Bicknell et al. 2014) and diseases and pest suppression (Molina et al. 2014). Because marginal lands have a lack of nutrients, poor organic matter and structure, the function of soil arthropods will contribute to C sequestration, nutrient mobilization, and turnover, maintaining soil fertility, and controlling pests (Plieninger and Gaertner 2011; Kang et al. 2013). For example, (Frouz et al. 2013) found positive correlation of soil faunal activity and C sequestration in mineral soils with low SOM content, such as soils in abandoned agricultural fields. The presence of diverse arthropod communities within the soil environment contributes to the intricate web of interactions and processes that shape soil functioning and sustainability (Lehmitz et al. 2020; Chiatante et al. 2021).

3 Soil Arthropods as Potential Indicators of Soil Health on Marginal Land

Improving degraded land productivity and quality should be based on meaningful measures that take soil conditions into account (Gibbs and Salmon 2015). Indicators are organisms or groups of organisms that may be used to assess the ecological condition of a particular ecosystem, and monitor the impacts of environmental stressors, (Koivula 2011; Simoni et al. 2021). According to Simoni et al. (2021), soil arthropods can be a useful tool for assessing the restoration or efficacy of management practices in agricultural lands and tracking changes over time. Numerous studies have included soil arthropod diversity and functions as key indicators of soil health (Niemelä 2000; García-segura et al. 2018; Chiatante et al. 2021). Soil arthropods i.e., ground beetles (Work et al. 2008), spiders (Lehmitz et al. 2020), ants (Andersen et al. 2002; Peters et al. 2016), and dung beetles (Bicknell et al. 2014), as well as earthworms (Baldivieso-Freitas et al. 2018), collembola (Fiera et al. 2020), and acari (Durbešić et al. 2006; Gerlach et al. 2013) are considered indicators of soil quality, due to their high abundance and diversity, ease to sample, and rapid response to ecological changes (Fiera et al. 2020; Gerlach et al. 2013; Méndez-Rojas et al. 2021; Pfiffner 2004; Schirmel et al. 2015). They are ecologically well-known for being vulnerable to agricultural disturbances such as pesticide use, and frequent tillage practices (da Luz et al. 2019). As a result, soil arthropods could be used as important ecological indicators for monitoring soil quality in marginal lands (da Luz et al. 2019) thereby enhancing agricultural productivity (Muscat et al. 2022).

3.1 *Role of Arthropods in Soil Fertility*

Soil arthropods are fundamentally important in farms as they can serve as biological indicators of soil quality and ecological functions (Culliney 2013; Bagyaraj et al. 2016; Suheriyanto et al. 2019). In soil fertility, arthropods are involved in litter decomposition, nutrient cycling and mineralization, and humification of organic matter (Culliney 2013; Bagyaraj et al. 2016; Roy et al. 2018; Menta and Remelli 2020). In addition, arthropods influence the formation and stability of soil structure (Culliney 2013).

A detailed review of the effects of arthropods on soil fertility is outlined by Culliney (2013), Neher and Barbercheck (2019), Roy et al. (2018) and Menta and Remelli (2020). What can be taken from all the above reviews can be summarized as follows: (a) Soil arthropods feed on litter and convert it into faeces which are integrated into soil organic matter. (b) The arthropods' faecal material contains available plant nutrients. (c) The arthropods' faeces are important in the formation of soil aggregates and increase soil fertility status. (d) Arthropods are involved in the decomposition and stabilization of soil organic matter. (e) Presence of arthropods increase soil microbial activities due to increase in energy substrate during litter decomposition.

3.2 *Ecosystem Services of Biological Pest Control*

Above-soil arthropods are widespread soil predators in agricultural lands. They provide ecosystem services such as biological control of pests (Saqib et al. 2020), and weed seeds population control (Volkmar et al. 2003), which contributes substantially to crop production (Rowe et al. 2013). Above-soil arthropods are referred to as ground-dwelling predators because they are diverse on the ground and have a limited ability to disperse (Corcos et al. 2021; Ziółkowska et al. 2021). For example (Birkhofer et al. 2018) found that among the analysed communities of predaceous arthropod taxa, spiders, ground beetles, and rove beetles were significant positive indicators for biological pest control.

Ants are generalist predators that feed on a range of pests, but they also influence soil movement, nitrogen cycling, and water availability in their environments (Tiede et al. 2017; Santoandré et al. 2019). Ground spiders, carabids, and rove beetles also exhibit important trophic roles in the food webs, either as predators, decomposers, or phytophagous (Krooss and Schaefer 1998; White et al. 2007; Torma et al. 2019). Among above-soil arthropods, ground beetles are the most numerous and essential seed predators (Honek et al. 2003). Protecting and supporting a diverse range of above-ground predators may promote integrated pest management on intact agricultural fields (Aguilera et al. 2020; Bianchi et al. 2006; Holland et al. 2014).

4 Agricultural Management Practices That Enhance Soil Arthropods in Marginal

Agricultural soil management practices are putting pressure on soil arthropods and the ecological services they offer. According to research, agricultural intensification is the main cause of the decline of both above and below soil biodiversity (Tilman 1999; Flohre et al. 2011; Lessard-Therrien et al. 2018), with consequences for the functioning and sustainability of agricultural lands (Tschamntke et al. 2012). Intensive management, particularly pesticides and tillage methods, has detrimental effects on soil arthropods, either directly by reducing their mortality and survival (Baldivieso-Freitas et al. 2018; Gailis et al. 2017; Krooss and Schaefer 1998; Vician et al. 2018), or indirectly by modifying habitat for shelter and food resources (Holland and Luff 2000; Lami et al. 2020). Such disturbance in agricultural lands alters soil parameters, such as pH, water content, total organic carbon, and microbial characteristics, which affect crop production (Kanianska et al. 2016; Frouz 2018; Massaccesi et al. 2020). As a result, it is crucial to advocate for sustainable management approaches that promote the effectiveness of natural resources, such as biological productivity, nutrient cycling, and carbon sequencing (Brévault et al. 2007). Such practices would be beneficial for the conservation of soil biodiversity and their associated ecosystem services by restoring structure and function to degraded lands (Schröder et al. 2022).

Conservation agriculture is one of the farming practices that has been considered to promote self-regulating systems and higher biodiversity (Baldivieso-Freitas et al. 2018; Brévault et al. 2007; Diehl et al. 2012; Gayer et al. 2019), due to reduced soil tillage, crop rotations, permanent soil cover, and less inputs of agrochemicals (Njaimwe et al. 2016; Malobane et al. 2020). Several studies have so far produced empirical evidence that conservation farming approach enhances soil species biodiversity and their ecosystem functions (Petit et al. 2017; Gayer et al. 2019; Lami et al. 2020; Massaccesi et al. 2020). For instances, with the cultivation of legumes, and the maintenance of crop residues through rotating crops, conservation farming reverts land degradation, enhances nitrogen availability, and increases soil fertility (Kang et al. 2013; Pustkowiak et al. 2018). Another advantage is the suppression of weeds and pests (Plieninger and Gaertner 2011; Bonini Da Luz et al. 2019).

A study by Chikoski et al. (2006) found that the abundance of arthropods differs across seasons and water application can favour some arthropods while affecting others. Thus, it is important to know the arthropod species in any field before planning water management to enhance their activities and abundance. Organic farming turns to favour the diversity and abundance of arthropods compared to conventional agricultural (Ponce et al. 2011; Tsutsui et al. 2018; Suheriyanto et al. 2019; El-Shafie 2022). Intercropping, crop rotation and cover crops were also reported to enhance arthropods' diversity and abundance (Chen et al. 2019; Meyer et al. 2019; Martinez et al. 2020; Brandmeier et al. 2021; El-Shafie 2022). In addition, the application of organic amendments was found to enhance the diversity and abundance of arthropods (Shanker et al. 2012; Mashavakure et al. 2021; Xu et al. 2022). The implementation of no-till and crop residue retention was also reported to enhance arthropods compared to conventional tillage (Sapkota et al. 2012; Pretorius et al. 2018; Rosario-Lebron et al. 2018; Menta et al. 2020). Above mention agricultural practices not only enhance arthropods but also enhance soil organic carbon which is important in achieving food security in Sub-Saharan Africa (Lal 2004, 2015). Therefore, the implementation of conservation farming practices on marginal lands can enhance the synergistic effects of soil arthropods (Chiatante et al. 2021; Mayer et al. 2021), thereby improving sustainability and productivity (Ponge et al. 2013). Despite the importance of the above-mentioned practices, the abundance and diversity of arthropods are site-specific (Menta and Remelli 2020).

5 Conclusion

Arthropods are fundamentally important in soil ecosystems and functions. Studies reviewed show that arthropods are important in enhancing soil quality, thus, they can assist in the restoration of marginal soils. Agricultural practices that enhance arthropods include no-till, crop rotation and diversity, application of organic amendments and crop residues and organic farming. The same practices increase soil organic carbon. We conclude that the implementation of agricultural practices that enhance soil organic carbon sequestration as a basis for achieving food security in

Sub-Saharan Africa will also enhance arthropods' diversity and abundance. However, local studies are recommended as the response of arthropods to these practices is site specific.

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Enhancement of Soil Arbuscular Mycorrhizal Fungi: A Step Towards Restoring Marginal Soils



M. E. Malobane and M. R. Madzivhandila

1 Introduction

Soil quality is vital in supporting and sustaining life on Earth (Bertola et al. 2021). As outlined in the United Nations' sustainable development goals (SDGs), soil is linked to numerous SDGs (Montanarella and Alva 2015; Bouma et al. 2019; Lal et al. 2021; Evans et al. 2022), for instance: SDG 1: End Poverty, SDG 2: Zero Hunger, SDG 3: Good Health and Wellbeing, SDG 6: Clean Water and Sanitation, SDG 7: Affordable and Clean Energy, SDG 9: Industry Innovation and Infrastructure, SDG 11: Sustainable Cities and Communities, SDG 12: Responsible Consumption and Production, SDG 13: Climate Action, and SDG 15: Life on Land (Lal et al. 2021). In addition, the restoration and strengthening of local food production systems post-Covid-19, will mainly rely on soil quality (Lal et al. 2020). It safe to say that human beings strongly rely on soil capacity to produce food, as approximately 95% of food comes from the land (Food and Agriculture Organisation [FAO] 2015). Thus, it is important to conserve and enhance soil quality (Lal et al. 2021; Saurabh et al. 2021).

Despite the importance of soil in sustaining life on Earth, numerous studies have shown that soil quality is declining, due to anthropogenic activities and climate change (Delgado-Baquerizo et al. 2016; Wu et al. 2017; Borrelli et al. 2020). This has raised significant concerns about how food production will keep up with the current escalating rate in population growth (Maisonet-Guzman 2011; Fraser 2020; Macke et al. 2021). Marginal lands are currently viewed as a possible solution for expanding agriculture in an effort to guarantee food security for growing populations around the world (Shahid and Al-Shankiti 2013; Ahmadzai et al. 2021; Kuang

M. E. Malobane (✉) · M. R. Madzivhandila
University of South Africa, Department of Agriculture and Animal Health,
Florida, South Africa
e-mail: malobme@unisa.ac.za

et al. 2022). Unfortunately, marginal lands are generally characterised by lower quality, and are deemed to have less economic value (Shahid and Al-Shankiti 2013; Mehmood et al. 2017; Pulighe et al. 2019). In addition, such lands receive limited rainfall and are prone to extreme temperatures, which affect food production on them (Liu et al. 2011; Shahid and Al-Shankiti 2013). For those reasons, marginal soil restoration is vital for agricultural expansion aimed at meeting global food security needs (Malobane et al. 2020).

Soil microbiotas play a crucial role in soil quality, ecosystems and functions (Lori et al. 2017; Mohamed et al. 2021), being involved in the cycling of nutrients and carbon in the soil (Horwath 2017; Jiao et al. 2019; Wu et al. 2020; Mohamed et al. 2021). Some soil microbiotas are involved directly or indirectly in facilitating soil-based chemical and physical processes (Khosro et al. 2011; Costa et al. 2018; Mącik et al. 2020; Chen et al. 2021). Research has shown that an increase in certain soil microbiotas leads to enhanced soil quality and crop yields (Jacoby et al. 2017; Mącik et al. 2020; Singh et al. 2020; Raymond et al. 2021). In addition, soil microbiotas can help crops to tolerate certain abiotic stresses (Hashem et al. 2019; Ullah et al. 2019; Kumar et al. 2020; Koza et al. 2022). The literature also shows that some soil microbiotas can assist crops to fight against certain diseases (Arif et al. 2020; Oleńska et al. 2020; Pascale et al. 2020).

Arbuscular mycorrhizal fungi (AMFs) are important soil microbiota (Rocha et al. 2019; Zhang et al. 2019; El-Sawah et al. 2021; Jajoo and Mathur 2021). Arbuscular mycorrhizal fungi are regarded as amongst the most abundant and diverse soil microorganisms that are significantly involved in soil quality (Lenoir et al. 2016; Lilleskov et al. 2019; Dagher et al. 2020). These fungi, which form symbiotic relationships with the crops on the root zone, resort under *Glomeromycota* phylum (Stürmer 2012; Stürmer and Kemmelmeier 2021). Research shows that AMFs are involved in processes that enhance soil quality and productivity (Alguacil et al. 2014; Parihar et al. 2020; Fall et al. 2022) as well as crop yields, and are tolerant to abiotic stress (Igiehon and Babalola 2017; Begum et al. 2019; Malhi et al. 2021). In addition, AMFs can assist in reducing soil pollutants (Dagher et al. 2020; Lee et al. 2020; Riaz et al. 2021). This makes AMFs ideal soil microorganisms to promote in marginal soils, with a view to enhancing the production capacity of those soils. The current chapter seeks to highlight the importance of AMFs in restoring soil productivity, particularly in conditions that exist under marginal soils. In addition, the focus here is on the agricultural practices that promote AMFs in soils.

2 The Impact of Arbuscular Mycorrhizal Fungi on Soil Quality

As stated by Andrews et al. (2002), soil quality is one of the key constituents of environmental quality, besides the quality of the air and water. Soil quality is made up of physical, chemical and biological properties, therefore enhancing one of the

soil properties will have a direct influence on soil quality status (Lal 2015, 2020). An improvement in soil quality has been reported to enhance crop yields (FAO 2015; Naab et al. 2017; Yu et al. 2019).

2.1 The Effect of AMF on Soil's Physical Properties

Arbuscular mycorrhizae fungi have benefits for the physical properties of soils (Fall et al. 2022), mainly through their hyphae and the production of glomalin-related soil protein (GRSP) (Yang et al. 2017; Sidhu et al. 2019; Singh et al. 2022). AMF hyphae physically bind soil aggregates together, while GRSP acts as a binding agent (Borie et al. 2008; Lehmann et al. 2020; Wang et al. 2021a). The main functions of AMF hyphae and GRSP occur at the soil aggregate level (Singh et al. 2017; Zhu et al. 2019; Wang et al. 2021a). For this reason, many studies have reported that an increase in AMF spores, hyphae and GRSP correlates with an increase in soil aggregate stability (Yang et al. 2017; Ji et al. 2019; Ai et al. 2022). In turn, an increase in soil aggregate stability is linked to enhanced water infiltration, reduced loss of nutrients and organic matter, and lower greenhouse gas emissions (He et al. 2019; Liu et al. 2019; Parihar et al. 2020; Bhattacharyya et al. 2022).

A study by Syamsiyah and Herawati (2018) found that soils inoculated with AMF had higher aggregate stability than those which were not inoculated: an increase in aggregate of up to 5%. That study was conducted in soils with soil organic carbon (SOC) of less than 1% and low fertility status (Syamsiyah and Herawati 2018)—soils with an SOC below 2% and low fertility status are generally regarded as marginal (Mandiringana et al. 2005; Nabel et al. 2016). A study conducted by Malobane et al. (2021), into marginal soils in South Africa, found that an increase in aggregate stability was associated with an increase in GRSP. In addition, many studies concur that AMFs have the potential to enhance the physical properties of soils regarded as marginal (Kohler-Milleret et al. 2013; Yadav et al. 2017; Barna et al. 2020; Ai et al. 2022; Singh et al. 2022). Thus, AMFs and their products are fundamentally important in restoring the quality and functions of soils (Singh et al. 2022).

2.2 The Effects of AMFs on Soil's Chemical Properties and Plant Nutrients

AMFs influence soil's chemical properties through the mineralisation, solubilisation and acidification of organic compounds (Riaz et al. 2022). Among other beneficial effects of AMF on soil's chemical properties, their role in phosphorus (P) cycling is the most recognised (El-Sherbeny et al. 2022). Despite being abundant in most soils, between 20% and 80% of total soil P is organic, and unavailable for plant

uptake (Reusser et al. 2022). AMF increase P bioavailability through synergistic interaction with phosphate-solubilising bacteria (PSBs) (Fall et al. 2022). PSBs exude organic acids such as acid phosphatase that mineralises insoluble P into plant-available forms that the fungal extraradical mycelium can absorb and release to the host plant (Fall et al. 2022; Sharma et al. 2022a). A study by Boilard et al. (2019), on soil collected from non-arable land, revealed that AMF inoculation enhanced acid phosphatase activity by 5.92%, compared to non-inoculated soil. In addition to the fungal contribution to P cycling, AMFs play an important role in nitrogen (N) cycling, by capturing ammonium from the soil through the extraradical mycelium, thereby increasing N availability and reducing N losses through volatilisation (Zhang et al. 2022a). According to Caruso et al. (2018), AMF inoculation increased the N and P concentration of durum wheat by 22.8% and 32.5% respectively, compared to non-inoculated control soils in a study carried out in marginal soils.

Another beneficial function of AMFs is the acidification and dissolution of chemically bound nutrients through the enhanced production of organic ligands, siderophores (Burghelae et al. 2018) and low-molecular-weight organic acids (Andrino et al. 2021). For instance, Ezzati Lotfabadi et al. (2022) indicate that the AMF colonisation of soybean grown under severe water stress improved the concentrations of grain P and zinc, leaf potassium, and copper and stem manganese, relative to non-colonised soybean. Marginal soils are generally characterised by water scarcity, coupled with a low infiltration rate and water-holding capacity (Malobane et al. 2020). Several studies have demonstrated the potential of AMFs in improving the chemical composition of marginal soils (Bertham et al. 2019; Ren et al. 2019a; Abou El-Gould 2020; Indriana et al. 2021).

Arbuscular mycorrhizae fungi association improves plant nutrition (Khaliq et al. 2022). The beneficial effect of AMF on plant nutrients has been attributed to various mechanisms, including an increased absorptive surface area within the host's root system, by the fungal extraradical mycelium extending beyond the nutrient depletion zone (Riaz et al. 2022); the ability of AMFs to break down inorganic compounds to plant-available forms (Tomer et al. 2021); better access to nutrients retained in the small soil pores through the fungal hyphae due to their thin size (0.1–0.5 mm) and the storage of excess nutrients in the vesicles (Hagh-Doust et al. 2022). Mycorrhizal plants differ from non-mycorrhizal plants in that the former acquire nutrients via two pathways: the direct pathway uptake (DPU) and the mycorrhizal pathway uptake (MPU) (Fall et al. 2022). In the mycorrhizal pathway, the extraradical mycelium acquire nutrients from the soil, translocate through the intraradical mycelium and release them into the symbiotic interfaces called arbuscules, where nutrient exchange takes place (Bhantana 2021). The mycorrhizal pathway is widely known to be more efficient in the uptake and use of mineral nutrients than the direct pathway (Bhantana 2021; Khan et al. 2022). A study conducted by Watts-Williams et al. (2021), under soil low in P concentration ($4.12 \text{ mg P kg}^{-1}$), revealed that AMF inoculation enhanced the uptake of zinc and iron by sorghum, when compared to non-AMF sorghum. Improved nutrient uptake efficiency increases photosynthetic rates, resulting in higher plant biomass production (Chandrasekaran

2022). Sarah et al. (2019) carried out a study in marginal soils with 0.032% N and 0.8 mg/kg P, and reported that mycorrhizal maize accumulated greater dry matter content (31.84 g) than non-mycorrhizal (5.098 g) maize. Various studies have reported increased plant nutrition by AMFs in soil characterised by nutrient deficiencies (Cobb et al. 2016; Saboor et al. 2021; Ortas and Bilgili 2022; Qi et al. 2022). Qiu et al. (2019) report that AMFs are important for soil reclamation and can increase total N, available P and K in degraded soils. Abdullahi et al. (2015) and Benaffari et al. (2022) report that AMF increase the efficiency of organic amended as a source of plant nutrients under soils with less than 1% SOC. This, because they increase the availability of plant nutrients derived from organic amendments (Rouphael et al. 2015; Wang et al. 2022). Notably, the efficiency of AMF on soil organic amendments as a source of nutrients is influenced by soil type (Abdullahi et al. 2015).

2.3 The Effect of AMFs on Soil's Biological Properties

AMFs are reported to influence soil's biological properties, by increasing some of the main components thereof. AMFs increase the production of soil glomalin and organic acid, which in turn enhance soil's organic carbon sequestration (Fall et al. 2022). A study by Wang et al. (2016), in coalfields with SOC less than 1% and low fertility status, found that AMFs can help to conserve SOC by up to 37%, compared to treatments without AMFs. An increase in SOC of up to 69% under AMF inoculation was also reported by several studies (Jeewani et al. 2021; Agnihotri et al. 2022; Singh et al. 2022; Zhang et al. 2022b). The increase in SOC is important for soil functions and behaviours (Lal et al. 2015). In addition, SOC sequestration can assist in achieving food security, as it improves soil quality and fertility statuses (Lal 2004).

Soil inoculated with AMF was found to have high catalase, urease and alkaline phosphatase compared to non-inoculated soils (Qiu et al. 2019), with such increases being central to the decomposition of organic materials, and N and P cycling processes (Li et al. 2019; Liu et al. 2021). These enzyme activities are also indicators of soil fertility and the regeneration of degraded soils (Joniec 2018). An increase in enzyme activities due to AMFs has been reported (Qin et al. 2020; El-Sawah et al. 2021; Fall et al. 2022).

3 The Effects of AMFs on Plant Growth

Several studies have reported that AMFs improve plant growth and yields under unfavourable conditions (Diagne et al. 2020; Chandrasekaran et al. 2021; Khaliq et al. 2022). A study by Sabia et al. (2015) found that AMF inoculation improved maize grain yields (4%), biomass (10.61%) and height (3.75%) under low agroeconomic inputs. Similar results were found by Wu et al. (2022), who reported that

AMF inoculations enhanced crop yield by 23% and biomass by 24.2%, compared to uninoculated treatments.

An increase in crop yields and performance after AMF inoculation was reported in many other crops such as tomato (Sellitto et al. 2019; Chandrasekaran et al. 2021), soybean (Marro et al. 2020; Sheteiwy et al. 2021; Wang et al. 2021b), potato (Lombardo et al. 2020; Yang et al. 2020), watermelon (Ren et al. 2019b; Ye et al. 2019), yam (Lu et al. 2015; Sharma et al. 2022b), cotton (Gao et al. 2020) and common bean (Eke et al. 2019; Al-Amri 2021). The application of AMF was also reported to enhance the quality of fruits (Zeng et al. 2014; Sellitto et al. 2019).

4 Agricultural Production Practices That Enhance AMF

The implementation of agricultural practices that enhance soil AMF is fundamentally important, as it directly improves soil quality and function (Fall et al. 2022). The application of a no-till approach, crop residue retention, crop rotation and diversity, and organic amendments, were all reported to increase AMF population in the soil (Fall et al. 2022; Orrù et al. 2021; Thapa and Mowrer 2022). Liu et al. (2022), who conducted a study into winter wheat, found that the implementation of a no-till approach, along with organic fertilizer, increased the relative abundance of AMFs and diversity, compared to conventional tillage with and without organic fertilizer. That study was conducted under soils with less than 1% SOC, which are classified as marginal (Liu et al. 2022). Many other studies have reported that the use of a no-till approach increases AMF abundance and root colonisation, when compared to conventional tillage (Helgason et al. 2010; Qin et al. 2017; Morimoto et al. 2018; Gu et al. 2020). The application of organic amendments was also found to increase AMF abundance and diversity (Jaison et al. 2011; Qin et al. 2015; Luo et al. 2017; Jiang et al. 2021). By contrast, the application of inorganic fertilizers was found to reduce AMF abundance and diversity (Liu et al. 2020; Xiang et al. 2020; Jiang et al. 2021). The adoption of organic farming was also found to enhance soil AMFs, compared to conventional agriculture (Wahdan et al. 2021). Crop residue retention and crop rotation were also reported to enhance soil AMF (Turmel et al. 2015; Bakhshandeh et al. 2017; Paravithana et al. 2021). The abovementioned agricultural practices that were found to enhance AMF, in turn also enhanced SOC, which is important in improving soil quality and achieving food security (Lal 2004, 2015).

5 Conclusion

AMFs remain amongst the most important soil microorganisms which enhance soil quality, function, crop yields and development. Notably, site conditions can influence the extent to which AMF enhance soil quality. The implementation of

agricultural practices that enhance AMF is fundamentally important in marginal soils, for enhancing soil productivity and ensuring food security. Local studies on the best practices for enhancing AMFs are, however, still needed in Africa, especially under smallholder conditions, in order to maximise the potential benefits of these lands.

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Sustainable Soilless Recirculating Hydroponics for Productive Use of Marginal Lands: A South African Context



Nadia Alcina Araya, Makgoka Given Moremi, Salmina Mokgehle, Motiki M. Mofokeng, Mantwampe Johleen Malaka, Manaka Makgato, Hintsa Tesfamicael Araya, and Beverly Mampholo

1 Introduction

Recirculating or recirculating hydroponic systems (those which rely on pumps to actively move the nutrient solution to the planting bed, with the remaining nutrients after root uptake being recovered and reused in the system) are well known for their potential to maximize crop production, resulting in increased yields and better quality of the produce (Maboko et al. 2017; Maboko and Du Plooy 2018; Mampholo et al. 2018; Araya and Moremi 2021; Moremi and Araya 2021). Such systems are able to sustain crop production continuously throughout the year, using controlled environmental fluctuation techniques, thus limiting or eliminating the influence of harsh weather conditions. In addition, hydroponic production is generally less labour intensive, since it does not require cultural operations, such as ploughing, weeding and soil fertilization. These systems can also be put up anywhere near the markets and, as a result, the fresh produce can have better marketable qualities due to reduced transportation distances, especially for highly perishable vegetables. Compared to conventional soil cultivation methods, hydroponic systems are

N. A. Araya (✉)

Agricultural Research Council-Vegetable, Industrial and Medicinal Plants, Pretoria, South Africa

Agricultural Research Council, Natural Resources and Engineering, Pretoria, South Africa

e-mail: IbraimoN@arc.agric.za

M. G. Moremi · M. M. Mofokeng · M. J. Malaka · H. T. Araya · B. Mampholo

Agricultural Research Council-Vegetable, Industrial and Medicinal Plants, Pretoria, South Africa

S. Mokgehle

School of Agricultural Sciences, University of Mpumalanga, Mbombela, South Africa

M. Makgato

Agricultural Research Council, Infruitec-Nietvoorbij, Stellenbosch, South Africa

generally more efficient in terms of land, water and nutrient use, and are often less susceptible to the incidence of pests and diseases due to lower crop exposure to environmental stresses (Treftz and Omaye 2015). In such systems, crops can be produced on non-arable land, including poor soils having high salinity levels (Putra and Yuliando 2015). Due to their ability to suppress substrate drainage, runoff and evaporation to some extent, recirculating hydroponic systems have the potential to decrease water use by up to 90% compared to conventional systems, as water can be recycled and reused into the system, thus contributing to water footprint reductions (Barbosa et al. 2015).

Recirculating hydroponic systems, such as the gravel and nutrient film techniques are the most used, not only in South Africa (Maboko et al. 2017; Maboko and Du Plooy 2018; Mampholo et al. 2018; Araya and Moremi 2021) but worldwide (Runia and Amsing 2001; Raimondi et al. 2006; Ramírez-arias et al. 2018; Puspitahati et al. 2022). In South Africa, plants that are grown in the gravel film technique, have their root system supported in gravel, which is a well-drained inorganic substrate; whereas, in the nutrient film technique, plants often grow in net cups filled with both organic (mostly cocopeat and expandable clay pebble) and inorganic substrates (mostly perlite and Rockwool), with the main difference being that in the former the nutrient solution is continuously recirculated through the system, while in the latter the nutrient solution can be recirculated continuously or intermittently as a result of higher water holding capacity of the substrates utilized for production. Recirculation of water on a regular basis, as opposed to a continuous water flow, may be an advantage for the improved nutritional content of the crop, especially for fruiting vegetables like strawberries and cherry tomatoes, however, it requires a more complex system set-up, involving a timer to regulate water cycles based on crop water requirements. The gravel film technique is often implemented horizontally, while the nutrient film technique is conducted both horizontally and vertically. Both techniques are most suitable for the production of leafy crops under protected environmental conditions.

Recirculating hydroponic systems generally operate in protected hydroponic structures to lower the effects of extreme weather conditions on plant growth and to minimize maintenance of the systems. Water is continuously recaptured and recirculated to the crops using an irrigation pump. Thus, several important factors need to be considered to ensure adequate management of these systems, including fertilization scheduling, management of the nutrient solution and pests and diseases control. Thus, this book chapter aims at providing an overview of important production factors in recirculating hydroponics, typical crop yields, and water use efficiency obtained under South African conditions while emphasizing potential focus areas for research to improve the profitability and sustainability of crop production in soilless recirculating hydroponic systems.

2 Soilless Recirculating Hydroponics as a Solution to Optimize Unproductive (Marginal) Land Utilization

Due to the growing population and occurrence of weather extremes caused by climate change, more efficient and sustainable land utilization agricultural practices have become crucial in South Africa. The country is home to 60.6 million people, with the most populated provinces being Gauteng with 15.7 million and KwaZulu Natal with 11.7 million people (Stats SA 2023). As the smallest province of South Africa (total land area of 17,000 km²), Gauteng also registers the highest population density in the country (809.6 people per km² of land), with 97.2% of the total population residing in urban areas (Stats SA 2023). Due to the rapid population increase over the years, the province is faced with severe pressure on the limited available water resources. As a result of water scarcity in the country, priority is given to the domestic sector, leaving little amounts available to agricultural crop production activities. This calls for a need to develop and promote climate-smart agricultural technologies, which are space- and water-efficient. The Agricultural Research in collaboration with the Water Research Commission have explored innovative, resource-efficient recirculating hydroponic technologies to maximize crop yields per unity water utilized for production. These technologies were introduced, for the first time, to emerging commercial farmers in the Gauteng Province of South Africa (Fig. 1). The systems were established in farmers' home garden yards, where the available land was not suitable for conventional open-field crop production systems, because of their size, topography, or location. Fruity vegetables, such as tomato, use a maximum of 1 L of water per day per plant, while leafy crops such as lettuce, sweet basil and coriander use a maximum of 0.2 L of water per day per plant. This contributes to approximately 90% of irrigation water savings, while producing at



Fig. 1 Recirculating hydroponic systems successfully established and implemented at two farmers' sites in Zuubekom, Johannesburg district municipality of Gauteng Province of South Africa (pictures taken by Nadia Araya)

least double the yield particularly for leafy vegetable and herb crops (200 spring onion heads per m² unit area), thus offering a promising approach for increased income generation of farmers.

3 Soilless Recirculating Hydroponic Systems Commonly Used in South Africa

Nowadays, food crop production activities in South Africa have increasingly trended towards modern soilless cultivation technology, extensively used in greenhouses. Over the years, there have been attempts to eliminate a wide range of challenges in soil-type open-field production, due to variations in air temperatures, soil water holding capacity, cation exchange capacity, salinity, soils contaminated with heavy metals, limited nutrient supply, improper root aeration as well as a proliferation of pests and diseases (du Plooy et al. 2012), which are further exacerbated by climate change. Soilless production was successfully adopted to alleviate some of these problems, while giving the farmer better control over plant growth and development through the hydroponic cultivation system. Major advantages of the hydroponic cultivation system include high yielding food crops, efficient use of nutrients customized to plant needs, weed-free plants, relatively low incidence of pests and diseases, high nutritional and profitable quality of fresh produce under limited space (Mampholo et al. 2018). Table 1 shows a comparison amongst various recirculating hydroponic systems commonly used in South Africa.

4 Recirculating Hydroponic Systems Management and Maintenance

4.1 Nutrient Solution

Nutrients are one of the basic requirements of any hydroponic system (Kozai et al. 2018). They are the natural fuel for plant growth (Hosseinzadeh et al. 2017). In recirculating hydroponic systems, essential elements are supplied to crops by dissolving soluble fertilizers in water to make up the nutrient solution (Resh 2022). In this regard, water-soluble fertilizers are added to the irrigation system, and the nutrient solution is supplied to crops through fertigation. In general, the mineral composition of a nutrient solution should consist of macro-elements such as nitrogen, phosphorous, potassium, calcium, magnesium and sulphur and micro-elements such as iron, manganese, boron, copper, zinc and molybdenum (Marschner 2011) which are essential for crop growth and development. Macro-nutrients are needed in relatively large amounts, whilst micro-nutrients or trace elements are needed in small amounts.

Table 1 Recirculating hydroponic systems commonly used in South Africa

Characterization according to various aspects	Recirculating hydroponic system			
	Gravel film technique (GFT)	Nutrient film technique (NFT)	Ebb-and-flow	Deep-water-culture
Definition	Media-based grow bed system, in which a film of nutrient solution continuously flows down gravel beds by gravitation (Maboko et al. 2017)	Liquid-based grow tray system, where plants are often grown in net pots filled with growing media such as perlite, cocopeat or Rockwool that hold the plant roots (Sihlongonyane 2020)	Media-based grow bed system, in which plant roots are anchored within a thick layer of substrate (usually gravel) that is periodically flooded with a nutrient-rich solution before draining back into a reservoir (du Toit 2022)	Liquid-based system, in which the nutrient solution is held in a reservoir where the plants are suspended in deep, well-oxygenated water enriched with nutrients (du Toit 2022)
Support media for plant roots	Gravel substrate	Perlite, cocopeat, expanded clay pebbles or Rockwool substrate	Usually gravel substrate	Polystyrene trays
Advantages	Ideal for large-scale commercial production High density planting Suitable for a wider range of crops	Ideal for large-scale commercial production Allows intermittent recirculation of nutrient solution, making it possible to schedule irrigation and save energy consumption Crops can be grown vertically Reduced evaporation compared to other systems Ideal for shallow-rooted crops, with short growing season and low fruit load	Relatively easy to install and operate on a small-scale Allows intermittent recirculation of nutrient solution, making it possible to schedule irrigation and save energy consumption Suitable for a wider range of crops	Ideal for large-scale commercial production Ideal for shallow-rooted crops, with short growing season and low fruit load No substrate required
Disadvantages	Susceptible to water-borne diseases Increased water evaporation	Susceptible to water-borne diseases	Susceptible to water-borne diseases Increased water evaporation	Susceptible to water-borne diseases

(continued)

Table 1 (continued)

Characterization according to various aspects	Recirculating hydroponic system			
	Gravel film technique (GFT)	Nutrient film technique (NFT)	Ebb-and-flow	Deep-water-culture
Suitable crops	Leafy and fruity vegetables and herbs	Leafy vegetables and herbs	Leafy and fruity vegetables and herbs	A limited range of leafy vegetables and herbs, such as lettuce, spring onion and microgreens

A hydroponic recirculating system is one in which the nutrient solution is recovered and recycled through the system continuously. A well-balanced and improved nutrient supply is necessary for productive use of resources by crops grown hydroponically, not only to ensure a high yield but also to guarantee the quality of the edible tissues. Because of the limited nutrient-buffering capacity in recirculating hydroponic systems, close monitoring of the system is important. The amount and rate of application of the nutrient solution depend on the crop and growth stage, the type of growing media, the irrigation system and the prevailing environmental conditions. In recirculating hydroponic systems, the management of nutrients is vital and must be done efficiently as possible to increase productivity while preserving the environment. Nutrient management involves applying the right source of fertilizer (e.g., ammonium or nitrate as nitrogen source) and according to plants needs and growth stage, as well as environmental conditions. The main idea of crop nutrient solution management is to avoid over-application of nutrients, which ultimately prevents loss because of low yield resulting from the toxicity of certain nutrients caused by unnecessary use of fertilizers. Nguyen et al. (2021) reported a strong variation in ion ratios present in the nutrient solution and those absorbed by plants which led to the accumulation of certain ions in the nutrient solution. This caused an imbalance of mineral elements in the nutrient solution and created more energy to absorb the suitable ions. The reusing and recirculation of nutrient solutions in recirculating hydroponic systems presents a plan to prevent groundwater and environmental pollution in addition to reducing fertilizer costs.

In recirculating systems, the plant roots are vulnerable to a continuous supply of recirculating water and minerals (Sharma et al. 2018). Depending on the stage of plant development, some elements in the nutrient solution will be depleted more quickly than others, and as water evaporates from the nutrient solution, the fertilizer becomes more concentrated and can burn plant roots. Also, as the recirculation continues, the mineral nutrient solution will drop because of nutrient uptake by the plant roots. Consequently, the mineral content should be frequently replenished. Renata et al. (2018) has shown with lettuce plants cultivated in domestic wastewater that the reuse of exhausted nutrient solution may lead to the shortage of some key macro and micronutrients and their increased salinity (Bar-Yosef 2008) causing, in

turn, problems for crops (Carmassi et al. 2005; Parida and Das 2005). Thus, it is very important to have management practices that reduce salinity in recycled solutions and minimize the physiological impact of salinity on plants. In South Africa, practically, there are three important characteristics used to manage the nutrient solution, which are electrical conductivity (EC), pH and the nutrient concentration ratio.

The total salt concentration of a nutrient solution must be considered, and the nutrient solution electrical conductivity is defined as a measure of total mineral elements dissolved in a solution. The nutrient solution EC is an index of salt concentration, and an indicator of electrolyte concentration of the solution and is related to the number of ions available to plants in the root zone (Nguyen et al. 2021). It is mainly utilised to monitor the application of fertilizers. However, there is a limitation with the nutrient solution EC which is that it only indicates the total concentration of the solution and not the individual nutrient components present in the plant. When plants take up nutrients and water from the solution, the EC of the solution changes. If the EC is higher than the recommended range, fresh water must be added to reduce it. If it is lower, add nutrients to raise it. It is important to manage the nutrient solution EC level because very low concentrations of mineral elements often lead to nutrient deficiencies, retard plant growth and yield, whereas too high mineral concentrations result in toxicity or nutrient-induced deficiency. Moreover, higher EC generally hinders nutrient uptake and induces osmotic stress, ion toxicity, nutrient imbalance, wastes nutrients, and increases the discharge of more nutrients into the environment, resulting in environmental pollution. Therefore, the estimation of individual nutrient requirements in different growth stages is needed for the replacement of the nutrient solutions during the growth period (Samarakoon et al. 2006). The ideal EC range for most hydroponic crops is between 1.5 and 2.5 dS/m, but this is influenced by crop specie and phenological stage (Nguyen et al. 2021). Too low and too high EC would reduce yields, visual quality, and phytochemical compounds, lead to a less attractive colour and taste to consumers, and enhance the negative health effects due to nitrate accumulation (Yang et al. 2021). The elevated EC may have negative effects on yield but can also positively affect the quality of the fresh produce, thus compromising any yield losses through the production of products with a high added value (Chrysargyris et al. 2021). For example, increasing the EC of the nutrient solution from 0 to 3 dS/m increased the yield of tomatoes and decreased as the EC increased from 3 to 5 dS/m because of increased water stress (Zhang et al. 2016). Yang et al. (2021) reported that photosynthetic properties, SPAD, leaf area, yield and dry weight increased with increasing EC from 1.2 to 1.8 dS/m for *Eruca sativa* grown in hydroponic systems. It is important to determine the suitable EC level of nutrient solutions with ion ratios suitable for growing plants (Nguyen et al. 2021). Combrink (1998) increased the EC of nutrient solution from 2 to 4 dS/m by adding NaCl at 20 meq/L to the solution with the intention of improving the taste of Daniela tomatoes grown in South Africa. The fruit's total soluble solids (°Brix) increased significantly, but the associated higher sugar percentage was due to less water being taken up (more concentrated fruit juice) and not due to better sugar production. This was reflected by an associated 30% reduction in yield and fruit

size. Optimal EC is crop specific and dependent on inherited genetic make-up environmental conditions. The inherited factors determine the basic quality specific to the crop and variety, while the environmental factors affect the realization of the inherited potential (Sonneveld and Voogt 2009). However, the upper levels of EC in nutrient solutions must be considered for each species since excessive EC values may decrease the osmotic potential of the nutrient solution and consequently result in delays in water transport from roots to fruits, with negative effects on fruit expansion and yield (Chrysargyris et al. 2021). For many leafy vegetables, there are already specific formulations used on a commercial scale for hydroponics, and the optimum EC levels for different crops grown in hydroponic recirculating systems are shown in Table 2. So, appropriate management of EC in hydroponics technique can give an effective tool for improving vegetable yield and quality (Sharma et al. 2018).

In a nutrient solution, pH value determines the availability of essential plant elements which greatly affects plant growth. It determines the availability of nutrients added to the solution for uptake by the plant. A range of pH values is required to be maintained to ensure the availability of all the nutrients for uptake by the plants (Mayavan et al. 2017). The optimum pH range for soilless culture nutrient solution is between 5.5 and 6.5, and it seems to be a range that supports normal plant growth and nutrient uptake for most hydroponically grown crops (Sharma et al. 2018; Maboko et al. 2011, 2017). Optimal pH for maximum growth varies between species, cultivar, substrate and climatic conditions. Several studies assessed optimum pH levels for hydroponically grown lettuce and reported decreased leaf length and width, dry shoot weight, leaf area, and stomatal conductance because of not maintaining the pH to a specified range (Yang and Kim 2020; Maboko et al. 2011; Cardoso et al. 2018). Changes in the pH of nutrient solutions is influenced by the differences in the extent of nutrient uptake by plants with respect to the balance of anions versus cations. When the anions are up taken in higher concentrations than cations, for example, nitrate, the plant excretes OH[−] or HCO₃[−] anions, to balance the electrical charges inside, which increases the pH value and this process is called physiological alkalinity (Cardoso et al. 2018). When the pH is outside optimum levels, nutrient disorders and growth disorders occur and some studies suggest that direct effects of pH appear to be detrimental only at extremes of acidity and alkalinity, and growth retardation and nutrient destruction in the conventional pH range are

Table 2 Optimum range of EC values for different crops grown in active recirculating hydroponic system (Source: Sharma et al. 2018)

Crop	EC (ds/m)	System
Strawberry	1.8–2.2	NFT
Spinach	1.8–2.3	GFT, NFT
Lettuce	1.2–1.8	GFT, NFT
Basil	1.0–1.6	GFT, NFT
Sage	1.0–1.6	GFT

NFT—Nutrient Film Technique, GFT—Gravel Film Technique

It can usually be attributed to pH dependent factors (Gillespie et al. 2020). The growth response to pH is species-specific and very limited information is available regarding the response of pH of commercial cultivars and species grown in hydroponics (Gillespie et al. 2021). Overall, the pH of the plant root environment affects the uptake of nutrients, nutrient availability, ion antagonism, ionic species present, and solubility of fertilizer salts (Gillespie et al. 2020).

The nutrient concentration ratio is also another one of the most important aspects in obtaining high-quality vegetable products, because it is the means through which nutrients dissolved in the water are placed at the disposal of the plants. Determining the most suitable nutrient concentration ratio is vital since it affects the partitioning of carbohydrate translocation to plant organs. The N:K (nitrogen: potassium) ratio influences the balance between vegetative and reproductive stages, because potassium plays important roles in the processes that regulate plant growth when the nitrogen availability is high. Nitrogen is crucial for the growth and development of plants by changing the source-sink relationship and, as a result, the distribution of assimilates between vegetative and reproductive organs (Yousaf et al. 2021). Potassium is the most extracted macronutrient by most vegetables, and it plays an important role in photosynthesis, formation and translocation of carbohydrates, and efficient use of water by the plant (Marques et al. 2018). Furthermore, it improves the weight gain and quality of the fruits and, as a result, their market value (Tohidloo et al. 2018). A deficiency of potassium generally causes a decrease in the rate of photosynthesis and an increase in respiration, resulting in a decrease in carbohydrate accumulation and fruit quality (Cerdeira et al. 2008; Marschner 2011). It has been shown that increasing nutrient solution K from 235 to 300 mg/L significantly increased yield of strawberries and fruit quality traits including vitamin C and total soluble solids (TSS) (Ebrahimi et al. 2012). The process is more complex in fruity vegetables, since it involves the vegetative and reproductive phases, and it is sometimes necessary to adapt the nutrient solution to the phases of the crop. In a study by (Cardoso et al. 2017) who evaluated four nutrition solutions with different N:K ratios (w/w) (1:0.5, 1:1.0, 1:2.0 and 1:3.0) in the reproductive phase of cucumber and reported greatest diameter yield with 1:3.0 ratio. Therefore, it is important to consider the nutrient formulation and the interrelationships of mineral elements in the solution with the growth stages of the crop during cultivation.

4.2 Growth Media Selection and Sterilization

Growth media is commonly used in hydroponics systems to support the development of a variety of plants, including vegetables, fruits, floriculture ornamentals, tree and shrub ornamentals and speciality plants. However, any of those systems should have the following qualities: (1) sufficient support for the plants; (2) appropriate distribution of air, since roots need oxygen and respire other gasses, such as carbon dioxide; (3) sufficient water availability for the plant roots; and (4) an accessible nutrient solution with consistent chemical characteristics. In South Africa,



Fig. 2 Gravel being used in South Africa as the plant growth substrate under the Ebb-and-Flow (left) and GFT (right) recirculating hydroponic systems (Pictures taken by Nadia Araya)

Table 3 Comparison between cocopeat and perlite growth media acquired in South Africa

Indicator	Buffered cocopeat	Expanded perlite
Average cost per L, vat inclusive (Rand)	10	7.5
Local availability	Available in local stores	Available in local stores
Bulk density (kg/L)	0.148	0.277
Water holding capacity (%)	69.1	40.5
Air filled porosity (%)	7.4	18.9
pH	5.76	6.84
Electrical conductivity (mSm)	103	145

gravel is the most common type of substrate used under the GFT (Maboko and Du Plooy 2018; Mampholo et al. 2018) and Ebb-and-Flow hydroponic systems (Fig. 2). There are several benefits associated to the use of gravel in hydroponics, including its easy affordability and local availability, promotion of good aeration to plant roots and increased structural durability, which allows it to be reused.

South African NFT systems, on the other hand, make use of organic or inorganic growth media. Cocopeat and perlite are the most commonly used, respectively. Table 3 shows a comparison between the two growth media, in terms of their cost, local availability, physical and chemical properties from sample materials acquired in South Africa. Such comparison can assist growers in making more informed decisions about the best choice of growth media for their NFT system. Cocopeat is slightly more expensive, holds more water and is lighter, but has lower air filled porosity, pH and EC than perlite. Thus, both have comparative advantages and disadvantages, but cocopeat is organic unlike perlite, which makes it biodegradable and more environmentally friendly compared to perlite.

Despite its notorious advantages, cocopeat as an organic growth media decomposes over time, creating a conducive environment for proliferation of diseases in recirculating hydroponic systems. Therefore, its sterilization is of utmost



Fig. 3 Sterilization of old cocopeat organic growth medium using hydrogen peroxide (left) and drying of the sterilized medium using solar radiation (right) before its reuse into the NFT hydroponic system (pictures taken by Nadia Araya)

importance prior to its reuse in order to minimize diseases incidence. Sterilization is often done using clean water, followed by the application of sporekill for the control of fungus or hydrogen peroxide for the control of bacteria. Figure 3 illustrates the process of old organic growth medium sterilization using hydrogen peroxide before its reuse into the NFT hydroponic system.

4.3 Sanitation

Sanitization is on-going maintenance, and in the most basic form; it is seen as keeping things clean and tidy. Spilled water, dead plant matter, air intake filters are all part of this regular maintenance, and they will have an overall effect on your system performance. In a hydroponic recirculating system, all contact surfaces and equipment that encounter flood water or plant material must be washed first and then disinfected. When drained nutrient solutions are re-used in closed systems, the risk of spreading pathogens is a real danger.

Sanitation in plants is a common practice to remove leaves as part of a regular pruning and training regime for vine crops. This is not only a good practice for balancing vegetative and generative (reproductive) growth, removing older leaves can help minimize disease incidence, as these leaves can be more susceptible to infection by diseases. Taking leaves that have been removed from plants can promote good sanitation. Beneficial insects may be on the foliage you are removing, so you can diminish your populations there. Diseased foliage should always be removed from the growing area. Aside from removing leaves from plants, you will want to remove any plant debris in the growing area, such as old flowers or leaves and leaflets that have fallen off plants. This debris can reduce the effectiveness of chemicals that may be used to sanitize surfaces. Additionally, weeds and vegetation growing around the perimeter of your growing facility should also be controlled, as these plants can harbour pests and diseases that could enter production facilities. Keeping



Fig. 4 Products used for disinfection of hydroponics management equipment (a), disinfection of equipment such as growing bags, cups or pots, pruning shears (b, c), Knapsack and its operation to disinfect an NFT hydroponic system operating under a plastic tunnel at ARC – VIMP (d, e) (pictures taken by Nadia Araya)

surfaces and equipment clean is another key aspect of any sanitation program. Surfaces in growing areas, such as walls, benches and floors, are essential to keep clean for preventing pest and disease infestations, as well as for food safety. When sanitizing any surface, be sure they are clean first. In addition to surfaces, sanitize equipment. Additionally, frequently sanitize pruning shears. For plants that are highly susceptible to viruses, sanitize pruners between every plant. Employees working with pruners can carry bottles of alcohol on their belts, and they can spray between each plant. Another approach is to keep a blowtorch handy and use heat to quickly sterilize tools. Other equipment, such as rafts from deep-water-culture techniques and troughs in nutrient-film technique systems, should be sanitized as often as is feasible and practical. Figure 4 illustrates some of the sanitation practices employed in hydroponics before and during crop growth.

4.4 Pests and Diseases Control

Food security challenges and decline in resources such as suitable arable land for cultivation has resulted in increased investment in alternative production systems such as soilless- and hydroponics systems. However, one major problem with such

intensive mono-cropping systems is an increased incidence of plant diseases and pests (Suárez-Cáceres et al. 2021). Pests and diseases in protected production systems can occur through contamination, inadequate phyto-sanitation protocols, or poor maintenance (Roberts et al. 2020). The microclimate conditions in protected environment provides warm and humid conditions which are suitable for development of diseases.

4.4.1 Common Pests and Diseases and Their Control in Soilless Production

Botrytis cinerea is a pathogen that causes severe yield losses in greenhouse production as it infects the leaves, stems, flowers and fruit of various vegetable crops (Zhu et al. 2013). Control of *Botrytis* disease has relied on fungicides such as benzimidazoles and dicarboximides; however, pathogen resistance to the chemicals due to intensive use and chemical residues has been a challenge (Zhu et al. 2013). Rotation of various fungicides with different active ingredients or the use of multi-fungicides, may be a solution to chemical resistance. *Pythium aphanidermatum*, which causes root rot in tomato, cucumber and spinach, spreads very quickly in the substrate with a very high water retention capacity and it is relatively not easy to control; however, commercial fungicides are available for use as preventative applications (Postma et al. 2005). Similarly, there are chemical fungicides to control powdery mildew, but continued use and residues of chemicals has provoked public attention to the negative effects on the environment and human health, thus a growing interest in environmentally friendly approaches to the pest and disease challenges (Wang et al. 2010).

Saleem et al. (2019) tested three commercially available biopesticides, Matrine, Spintoram, Azadirachtin, and custard apple seed extracts against aphids and spider mites on cucumber grown under hydroponics. Azadirachtin, which is a neem extract, showed 86% reduction and 86% efficacy against aphids, whereas the custard apple seed extract, Matrine, and Spintoram, had 94% and above reduction and more than 93% efficacy against the aphids (Saleem et al. 2019). Against spider, Azadirachtin had the lowest reduction of 51% and an efficacy of 31%, whereas the other three biopesticides showed a reduction of 86% and above, and the efficacy of more than 85% (Saleem et al. 2019). Overall the custard apple seed extract had the top most effect on both the aphids and spider mites. Table 4 provides a summary of options of organic and inorganic products used in soilless crop production.

4.4.2 Cultural Practices for Pests and Diseases Control in Soilless Crop Production Systems

Cultural practices such as manipulation of the microclimate in the plant canopy and around susceptible plant organs; prevention of inoculum entrance in the production area can also assist in disease control (Schnitzler 2004). For example, when

Table 4 Options of organic and inorganic products used for the control of selected pests and diseases in soilless crop production systems

Product name	Active ingredient	Pest/Disease	Crop	References
Prevasyn™	Capsicum extract, Garlic oil, Soybean oil	Thrips, mites, lepidopteran larvae, mealybugs	Vegetables	www.generalhydroponics.com
Margaret Roberts Organic Insecticide	Garlic juice extract, canola oil	Aphids, red spider mites, white fly	Herbs, vegetables	www.hydroponic.co.za
Ludwig Insect Spray	Garlic juice extract, canola oil, pyrethrin	Aphids, red spider mites, white fly, bollworm, thrips	Herbs, fruit crops, vegetables	www.hydroponic.co.za
Ludwig's rose spider mite spray	Etoxclzole	Spider mites	Tomatoes and roses	www.hydroponic.co.za
Biogrow Copper Soap	Copper and fatty acid	Powdery mildew, downy mildew, rust, late blight	Vegetables, fruits	www.biogrow.co.za
AllPerPlus Organic Leaf Wash	Clove oil, Rosemary oil, Quillaja saponin	Spider mites, Leaf miner, white fly, aphids, mould, powdery mildew		www.grohydro.co.za
San-O-Agri Extra	Sodium chloride, Hypochlorous acid	Botrytis, powdery mildew	Vegetables, Fruits	www.hydroponic.co.za
Biogrow Bioneem	Neem oil (azadirachtin)	White fly, mites, aphids, leafminer		www.biogrow.co.za
Makhro organicide Plus	Canola oil, Garlic extract, Pyrethrin, piperonyl butoxide	Broadspectrum insecticide	Vegetables, fruit trees, ornamental	www.makhro.co.za
Seizer 100 EC	Pyrethroid	Red spider mites, tuber moth, semi-looper	Tomatoes, ornamentals	www.makhro.co.za
Copper count N	Copper ammonium acetate	Bacterial blight, bacterial spot, powdery mildew, black spot	Vegetables, Fruits	www.hydroponic.co.za
Copstar 120 SC	Copper hydroxide	Bacterial spot, bacterial speck, early and late blight, downy mildew, bacterial spot, black spot	Vegetables and fruit trees	www.makhro.co.za
Odeon 720 SC	Chlorothalonin	Early and late blight, Botrytis rot, leaf spot, downy mildew, anthracnose, rust	Vegetables and ornamentals	www.makhro.co.za

(continued)

Table 4 (continued)

Product name	Active ingredient	Pest/Disease	Crop	References
Orius 250 EW	Tebuconazole	Powdery mildew, Black spot, Early blight	Vegetables and citrus trees	www.makhro.co.za
EcoBuz Larvae Pro	Crytoxin	Tomato leafminer, Fall armyworm, Bollworm		www.hydroponic.co.za

Table 5 Effect of imbalanced supply of nutrients on plant diseases experienced in soilless production systems

Nutrient	Crop	Effect on disease	Reference
Calcium	Beans	An increase in concentration significantly reduced grey mould	Schnitzler (2004)
Calcium	Tomato	Reduced the severity of leaf grey mould and fruit ghost spot	Schnitzler (2004)
Silicon	Cucumber	Reduced powdery mildew incidence	Schueger and Hammer (2003)
Silicon	Melon	Reduced powdery mildew incidence	Dallagnol et al. (2012)
Silicon	Strawberry	Significantly reduced the severity of powdery mildew	Kanto et al. (2004)

cucumbers were grown in non-heated polyethylene-covered structures, the disease incidence was significantly higher in the centre than closer to the opening (Schnitzler 2004). This shows the importance of ventilation in such structures. Although air circulation provides a cool and uniform temperature in the structure and aid in the management of diseases, it may also facilitate the spread of some diseases within the crop (Roberts et al. 2020). For example, lower relative humidity of 80%, which can occur when there is air circulation, was found to be more suitable for tomato powdery mildew development compared to a higher humidity of 95%, and this could be attributed to water films that prevent germination of the spores (Whipps and Budge 2000). In addition, the spores of *B. cinerea* and pests such as spider mites are mostly dispersed by air currents (Roberts et al. 2020). Canopy density also has a role in disease incidence in closed production systems. Cucumber plants with two stems had more disease incidence compared to single-stemmed plants (Schnitzler 2004). The microclimate around the two stem plants could have been suitable for the disease pathogen. This is an indication of the importance of plant spacing, removal of side branches, and prevention of massive vegetative growth to allow for air circulation and reduce humidity in the canopy is important. Pruning and removing leaves should be done carefully, not exposing the wound, which may lead to a stem infection.

Nutritional regimes can influence the susceptibility of plants to diseases (Kanto et al. 2004) (Table 5). Calcium applied at 1–3 mM on bean plant significantly reduces the grey mould incidence, whereas, at 5 mM, there was no reduction in the

disease severity (Kanto et al. 2004). Calcium-enriched tomato plants showed a 70% reduction in grey mould (Kanto et al. 2004). Calcium ions are known to strengthen cell membranes and reduce solute leakages, which is essential for preventing infections. Silicate application significantly reduced powdery mildew on melons, although root application was more effective than leave application and could be due to the increased silicon accumulation with root application (Dallagnol et al. 2012). Similarly, silicate applied at 25, and 50 mg/L significantly suppressed the powdery mildew disease in hydroponically grown strawberry, compared to the control of no silicate application (Kanto et al. 2004). Silicate applied on greenhouse-grown cucumber reduced powdery mildew incidence; however, it did not have an effect on fruit yield, thus no commercial gain (Schueger and Hammer 2003). The site of penetration for the powdery mildew pathogen is the trichome, and silicate accumulates in the trichomes, thus prevents penetration. Silicates also trigger the production of flavonoid phytoalexins, thus improving resistance to powdery mildew (Kanto et al. 2004). Various studies reported the susceptibility of tomato to grey mould under low levels of nitrogen, and beans fertilized with nitrate nitrogen were more resistant to grey mould compared to those fertilized with ammonium as a source of nitrogen (Schnitzler 2004). The suppression of *Phytophthora cactorum*, in the early stages, under aquaponics was suspected to be related to microbiological factors, while in hydroponics, the suppression of *Fusarium oxysporum* was due to the nutritional status of the plants (Suárez-Cáceres et al. 2021). Similarly, the disease-suppressive effect on non-sterilized rockwool was attributed to the microbial population (Postma et al. 2005). The study reported that filamentous actinomycetes, which were strongly correlated with the suppression of *Pythium* spp., might colonize dead roots in the medium and prevent *Pythium* entry, thus reducing the number of zoospores (Postma et al. 2005).

The pH of the nutrient solution and the root zone also seems to play a role in the suppression of some diseases. Slightly acidic pH (4.0–4.5) in the nutrient solution and pH of 5.0–5.5 in the root zones reduced the survival percentages of *Clavibacter michiganensis*, which causes bacterial canker in tomatoes (Huang and Tu 2001). This is an advantage since the pH can be easily manipulated in hydroponics systems to be unfavourable for the bacteria and maintained at a favourable root zone pH range of 5–6 for most crops. Basil plants grown in a nutrient solution with a pH of 4.0 showed reduced root rot disease incidence without negative effects on growth and yield (Gillespie and Kubota 2020). The effect of imbalanced supply of calcium and silicon on various horticultural crops is shown in Table 5.

Sanitation in a protected environment is important for disease suppression and reduction of the amount of initial inoculum. Removal of infected plants and plant debris throughout the season will reduce the disease incidence (Schnitzler 2004). Humidity and moisture build-up around the plants may provide conducive conditions for the development of diseases such as powdery mildew (Roberts et al. 2020). Ventilation to keep the environment dry is critical to restrict the spread of diseases like powdery mildew and grey mould (Schnitzler 2004). Ventilation to prevent excessive evaporation, coupled with the timing of irrigation, will also reduce the disease incidence. Hydrogen peroxide (H_2O_2) was found to control algal growth and

thus reduced the number of *Bradysia* spp. and *Scatella stagnalis* flies in lettuce production under hydroponics systems (Caixeta et al. 2018). However, H_2O_2 should be used with extreme care as it may negatively affect seed germination. Spinocyn insecticide, derived from secondary metabolites synthesized by soil actinomycetes, was also effective in suppressing the larvae of the flies (Caixeta et al. 2018). The fact that Spinocyn insecticides are an organic product with a broad-spectrum activity is an advantage for hydroponics production as it may control other pests.

Environmental factors, such as light, regulates the growth and development of fungi, including spore germination, hyphal extension and formation of reproductive structures (Zhu et al. 2013). Light quality can have a suppressive or promotive effect on disease incidence, and the effect differs between plant species. For example, the incidence of powdery mildew in cucumber plants was significantly reduced by red light but increased by purple, blue, green, and yellow light (Wang et al. 2010). However, green light reduced the growth rate of *B. cinerea* by reducing the spore germination, colony expansion and mycelial accumulation, thus the fungal biomass accumulation, while it did not reduce the growth rate of *Alternaria alternate*, *Fusarium oxysporum*, and *Magnaporthe grisea* on grapes and tomato fruits (Zhu et al. 2013). The suppressive effect of red light on powdery mildew in cucumber plants was correlated with salicylic acid-mediated defence mechanisms (Wang et al. 2010). Although the work by Zhu et al. (2013) was not done in a hydroponics system, the results show the possibility of using green light in controlling *B. cinerea* in such systems.

In soilless cultivation, it is easier to control exogenous factors favouring pests and diseases than in traditional soil cultivation. The chapter focused less on chemical control to promote more environmentally friendly approaches to climate-smart agriculture. Preventative measures like clean substrate, decontamination of greenhouse structures, and plant hygiene are important in managing pests and diseases in hydroponics. Regulating and manipulating the growth factors such as the nutrient status and root zone pH, training and pruning to improve canopy ventilation, overall ventilation to keep humidity levels low, and removal of infected or dead plant material will all contribute to the reduction of disease and pest incidences. Considering the effect of the chemical on the environment and human health, biopesticide development needs to be researched more.

4.5 Crop Selection

Crop selection is fundamental to successful production in active recirculating hydroponic systems. Many investigators have indicated that hydroponic recirculating systems cannot accommodate all crops, only certain types of crops are considered (Shai et al. 2021). Generally, small, relatively fast-growing plants with a short growing period are the most suitable crops for production in recirculating hydroponic systems (Olfati et al. 2012). This may be due to the recirculating systems design characteristics, which do not include a strong plant root support component

(Souza et al. 2019; Shai et al. 2021). Ideally, high economic value crops are greatly considered for these systems to ensure that the return on investment is assured within a relatively short period of time. In South Africa, the most popular crops produced under recirculating hydroponics are leafy vegetables, fruity vegetables and herbs (Niederwieser and du Plooy 2014).

Leafy vegetables are crops that have leaves as the edible organ of the plant; these include crops such as lettuce, Swiss chard, kale and cabbage (Niederwieser and du Plooy 2014). Such crops are very popular in home-gardening and low-quality markets such as hawkers and street vendors (Ratshitanga 2017; Velazquez-Gonzalez et al. 2022). Shai et al. (2021) reported that this might be due to their easy-to-cultivate growing characteristic.

According to Shai (2021), herbs are the most economically valuable, followed by fruity vegetable crops. Similar observation has been reported in other countries that, include the United States of America (Souza et al. 2019). Kaiser and Ernst (2016) justified the rise in consumer nutritious diversity considerations which increased herbs' popularity and acceptance in consumer diets. Although Souza et al. (2019) conceded that the market for herbs may be limited in emerging economies. Therefore, should a consistent and willing-to-pay premium market be established, herbs such as sweet basil, parsley, chives, mint, thyme, oregano, and watercress can be considered for production in recirculating hydroponics (Niederwieser and du Plooy 2014).

In terms of fruity crops, plants such as tomato, cucumbers, and peppers are common in the South African recirculating hydroponics industry (Niederwieser and du Plooy 2014). This is due to their ability to have multiple harvests and prolonged shelf-life characteristics, which ensure quick return on investment (Shai 2021). However, indeterminate cultivars may be challenging to grow in some recirculating hydroponics systems such as NFT. This is due to their height, deep root systems and heavy fruit load. Hence, despite the economic value of the crops, other factors are considered for the soilless recirculating production system. This consideration includes crop morphological characteristics that may disqualify some of the crops, as follows:

1. Plant height and vegetative vigour: large plants are difficult to support in a confined space, and difficult to increase plant density for higher yields. Furthermore, tall plants may experience interspecific competition for radiation. For instance, Maboko et al. (2011) reported that the high foliage of tomato resulted in increased vegetative growth, which affected the fruit size. Hence, growers often trellis and prune plants to overcome these challenges for better light interception and limit vegetative growth for enhanced fruit quality. Therefore, it is very important to select plants and crops that are small in size for production in active recirculating hydroponic systems;
2. Depth of root system: crops with long and thick tap roots, such as carrots, may not be suitable for recirculating hydroponics systems such as NFT due to limited area for root growth (Niederwieser and du Plooy 2014). Furthermore, crops with deep and highly branching tap roots can easily block water circulation, and ulti-

mately water and nutrient uptake by the crop are not suitable. Ideally, crops with relatively shallow rooting systems and short plant heights are recommended for production in active recirculating systems on a commercial basis. These include tomato, pepper, strawberry and cucumber. Crops with such morphological characteristics often do not perform well in the soil as the leaves, stems, and fruits can easily be damaged by harsh environmental conditions such as frost, wind and radiation, hence, they are suitable for hydroponic cultivation (Pulela et al. 2020; Maboko et al. 2011);

3. Stem tenderness: tender crops are often challenging to grow in active recirculating hydroponic systems. This refers to crops that need mechanical support in terms of trellising. Generally, they have herbaceous stems with a high fruit load to support them (Maboko and du Plooy 2008). Crops that need support include tomatoes, cucumbers, squash, and peppers, and these are often grown in open-bag hydroponic systems.

5 Water Use Efficiency: How Does South Africa Compare to the Rest of the World?

5.1 Leafy and Fruity Vegetable Crops

In recirculating hydroponics, water and nutrients are used efficiently due to the continuous recirculation pattern of the nutrient solution (Niederwieser and du Plooy 2014; Choi et al. 2016). In addition, recirculating hydroponics minimizes potential evaporation and has no runoff or drainage during the recirculating motion (Asaduzzaman et al. 2022). However, despite this recognition, literature still lacks extensive and scientific reports on crop water use efficiency (WUE), particularly under South African conditions (Pennisi et al. 2019; Singh et al. 2019; Abd-elhakim and Helal 2022; Shtaya and Qubbaj 2022). Therefore, there should be studies that signify the adoption of recirculating hydroponics productions with scientific backing for local conditions, and to date, there is only one study conducted in South Africa (Moremi and Araya 2021). Water use efficiency is defined as crop biomass or yield produced per unit of water that is used by the crop (Singh et al. 2019). It is a parameter that helps evaluate the efficiency of crops in converting each unit of water used into biomass or yield (Langenfeld et al. 2022). Water is absorbed in the roots and travels from roots to leaves, where it transpires. Transpiration is driven by vapour pressure deficit (VPD) which is a pressure gradient between water in the leaf and the atmosphere (Zhang et al. 2017).

Generally, investigators report that water use efficiency increases with an increase in temperature and reduced relative humidity (Singh et al. 2019). For instance, Rizk and Seidhom (2009) reported reduced water use efficiency (0.00931 kg/L) of strawberries in a naturally ventilated greenhouse, whereas Choi et al. (2016) reported increased water use efficiency (0.0603 kg/L) under controlled environmental

Table 6 Water use efficiency of vegetable crops under recirculating hydroponics systems implemented across a range of conditions

Crop	Water use efficiency (kg/L)	Hydroponic system	Growing conditions	Temperature (°C)	Relative humidity (%)	Country	Reference
Lettuce	0.075	NFT	Controlled greenhouse conditions	24.0–26.0	55.0–70.0	Italy	Pennisi et al. (2019)
Lettuce	0.012	NFT	Controlled greenhouse conditions	–	–	Palestine	Shitaya and Qubbaj (2022)
Cucumber	0.179	NFT	Naturally ventilated greenhouse	20.0–30.0	39.1–77.4	India	Singh et al. (2019)
Cucumber	0.167	NFT	Controlled greenhouse conditions	20.0–30.0	70.0–90.0	Egypt	Abd-elhakim and Helal (2022)
Mustard	0.079	DFT	Naturally ventilated greenhouse	–	–	Australia	Midmore and Deng-lin (1999)
Chinese Cabbage	0.046	DFT	Naturally ventilated greenhouse	–	–	Australia	Midmore and Deng-lin (1999)
Tomato	0.059	NFT	Controlled greenhouse conditions	17.3–33.3	53.2	Brazil	Rosa-Rodríguez et al. (2020)
Tomato	0.029	DFT	Naturally ventilated greenhouse	–	–	Australia	Midmore and Deng-lin (1999)
Strawberry	0.009	NFT	Naturally ventilated greenhouse	20.0–30.0	77.0–89.0	Egypt	Rizk and Seidhom (2009)
Strawberry	0.060	NFT	Controlled greenhouse conditions	7.4–22.9	60.0–90.0	Korea	Choi et al. (2016)

conditions. Similar results were reported for other crops, such as tomato and lettuce (Table 6) (Midmore and Deng-lin 1999; Rosa-Rodríguez et al. 2020). Thus, crops in naturally ventilated environments may have low water use efficiency when compared to crops grown in controlled greenhouse conditions (Pulela et al. 2020). However, temperature and relative humidity are not the only controlled environmental aspects in automated greenhouses; the system also controls radiation and, more recently, air composition in growth chambers (Kalantatri et al. 2017; Langenfeld et al. 2022). The effects of radiation are closely associated with temperature, as light intensity greatly affects temperature. The effects of air composition have been studied recently, and the results revealed that elevated CO₂ improves WUE by influencing partial stomatal closure, thereby improving biomass production while reducing transpiration (Langenfeld et al. 2022). Many studies have demonstrated a directly proportional relationship between WUE and stomatal conductance (Zhang et al. 2017; Bertolino et al. 2019). This is due to tight control of stomatal functions in crops when experiencing water stress.

Stomata are microscopic pores underneath the leaf that are responsible for plant ventilation. They are described as a gateway that facilitates CO₂ into the leaf mesophyll cells and the release of water and oxygen as by-products of photosynthesis (Bertolino et al. 2019). There are different shapes, densities and sizes of stomata, which may collectively be referred to as stomatal traits (Bertolino et al. 2019). These stomatal traits have been reported to have implications for stomatal conductance, transpiration and WUE in plants (Haworth et al. 2018). According to Bertolino et al. (2019), over evolutionary time, stomatal traits may have varied in efforts to help plants adapt to new environments (Drake et al. 2013). As a result, investigators use stomatal traits to genetically modify crops for increased WUE. According to Morales-Navarro et al. (2018), overexpressing SDD1-like gene from wild tomato reduced stomatal density and size in tomato leaves. The results demonstrated improved WUE and stomatal conductance in a controlled environment. However, Bertolino et al. (2019) caution against potential yield penalties when growing such plants in naturally ventilated environments or field conditions.

5.2 *Sweet Basil, Coriander and Thyme Herb Crops*

According to Pant et al. (2021), herbs WUE, like vegetable crops, is also affected mainly by environmental conditions as presented in Table 7. Da Silva et al. (2020) reported reduced WUE (0.0521 kg/L) for coriander due to uncontrolled greenhouse conditions, whereas Júnior et al. (2015) reported improved WUE (0.081 kg/L) by controlling environmental conditions. The WUE of sweet basil was also fairly low under South African conditions (0.014 kg/L) compared to that obtained in Brazil (0.065 kg/L), which could be attributed to differences in environmental conditions and hydroponic systems. Nonetheless, herb crops are known and treasured for their distinctive and diverse secondary metabolites. Secondary metabolites are special nonmetabolic complex compounds that are used for various functions that are

Table 7 Water use efficiency of herb crops grown under recirculating hydroponics systems across varying conditions

Crop	Water use efficiency (kg/L)	Hydroponic system	Growing conditions	Temperature (°C)	Relative humidity (%)	Country	Reference
Sweet basil	0.014	GFT	Shade net	23.0–33.0	50.0–63.0	South Africa	Moremi and Araya (2021)
Sweet basil	0.065	DWC	Temperature-controlled glasshouse	24.0–28.0	60.0–90.0	Brazil	Dos Santos et al. (2019)
Coriander	0.081	NFT	Temperature-controlled glasshouse	14.0–24.0	50.0	Brazil	Júnior et al. (2015)
Coriander	0.0521	NFT	Naturally ventilated greenhouse	19.0–35.0	40.0–96.0	Brazil	da Silva et al. (2020)
Thyme	0.0026	NFT	Naturally ventilated greenhouse	12.0–34.0	78.0	Jordan	Al-tawaha et al. (2016)

herb-specific and with great diversity. These compounds have excellent nutritious attributes for consumers. However, they are greatly affected by water consumption, as reported by a number of authors, the accumulation of these secondary metabolites is realized in moderate water-stressed plants (Pant et al. 2021; Da Silva et al. 2020). Hosseini et al. (2018) reported an increase in glycyrrhizin when Licorie herb was exposed to moderate water stress than when it was well watered. Nevertheless, these observations were reported under field conditions due to limited studies on recirculating hydroponics on this topic. It remains a huge gap in the literature, although information on the behaviour of secondary metabolites under controlled greenhouse conditions could be imperative for growers and scholars.

6 Conclusions

Soilless recirculating hydroponic crop production systems are gaining popularity in South Africa due to the decline in available arable land for agriculture. The most implemented methods are the gravel film technique (GFT), nutrient film technique (NFT) and deep-water-culture (D-W-C). For optimum performance, these systems need to be well managed and maintained in terms of mixing of the nutrient solution, growth media selection and sterilization, sanitation, pests and diseases control and crop selection. Without appropriate management, the warm and humid microclimatic conditions in protected environments may exacerbate the development of pests and diseases. Common pests and diseases in greenhouse environment include Thrips, mites, Aphids, white fly and Leaf miner (pests), powdery and downy mildews (fungal diseases) and bacterial spot, bacterial speck, early and late blight (bacterial diseases). Several options of organic (neem oil, canola oil, garlic oil, juice extract, clove oil, rosemary oil and capsicum extract) and inorganic products (Copper and fatty acid, Sodium chloride, Pyrethrin, piperonyl butoxide) are available to control such pathogens.

Ensuring appropriate management and maintenance of soilless recirculating systems contributes to increased crop productivity and input utilization efficiencies, particularly water and fertilizers. There is little to nonexistent information regarding water use efficiencies of vegetable and herb crops grown in soilless recirculating hydroponic systems, particularly under South African environmental conditions. Research that focuses on the development of optimum cultivation practices for high-value crops, environmental regulation in greenhouse production, and water flow patterns with particular emphasis on intermittent water flows, as these may induce the accumulation of secondary metabolites in high-value crops such as herbs, is still critical to increase water and nutrient use efficiencies in recirculating hydroponic systems. This would ultimately contribute to improved productivity and profitability of hydroponics farming, increased job creation and better preservation and conservation of natural resources such as land and water. A typical evidence-based case study was presented in this book chapter, to demonstrate the benefits of recirculating hydroponic systems for optimization of resource-use utilization on

unproductive/ marginal land of emerging commercial farmers in the Gauteng Province of South Africa.

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The Potential of Black Soldier Fly Frass to Revitalise Marginal Soils



C. Mubekaphi, Adornis Dakarai Nciizah, E. Dube, and M. Fanadzo

1 Introduction

1.1 *Brief Overview of Marginal Soils in Africa and Their Significance*

Marginal soils, characterised by their limited capacity for crop production due to various physical and chemical limitations, represent a significant portion of Africa's land area. These soils typically exhibit poor fertility, low water-holding capacity (WHC), low soil organic matter (SOM) content and a high susceptibility to erosion and acidification (FAO 2015). However, their extensive geographic spread and 'untapped potential' have positioned these lands as a focal point for discussion in the context of Africa's food security and land management. Sub-Saharan Africa, in particular, is estimated to have over 200 million ha of degraded land that can be classified as marginal soils (Wani et al. 2009). This degradation is typically due to a variety of factors such as parent material (inherent), population pressure, poor farming practices, and climate change. There is merit in technologies that can be adopted by farmers towards sustainable plant production on the marginal lands of Africa (FAO 2015).

C. Mubekaphi (✉) · E. Dube

School of Natural Resource Management, Nelson Mandela University, George, South Africa

A. D. Nciizah

Agricultural Research Council – Natural Resources & Engineering, Arcadia,
Pretoria, South Africa

Department of Agriculture and Animal Health, University of South Africa,
Florida, South Africa

M. Fanadzo

Cape Peninsula University of Technology, Wellington, South Africa

Despite their limitations, marginal soils will play a crucial role in the context of future agricultural development in Africa. They are, and will remain the primary resource base for the livelihoods of millions of resource-poor people, especially those engaged in subsistence farming (Lal 2009). With the continent's population predicted to double by 2050, placing additional demand on agricultural productivity, the management and revitalisation of marginal soils are of utmost importance (UN DESA 2019). Moreover, given the current trend of land scarcity, land reform and a strong movement towards sustainable farming practices in Southern Africa, the potential of these soils cannot be overlooked (Maltas et al. 2013). Properly managed, these lands can play a pivotal role in addressing societal issues related to land reform, food security, rural livelihoods, and biodiversity conservation in Africa.

1.2 Rationale for Using Black Soldier Fly Frass in Marginal Soils

The Diptera black soldier fly (*Hermetia illucens* L.) is of the Stratiomyidae family (Guilliet et al. 2022). They are originally from the tropical, subtropical, and northern regions of the Americas (Amrul et al. 2022). Frass is derived from waste excreted by the BSF larvae, comprising of mostly insect faeces, substrate residues, and exoskeletons (shavings) (Klammsteiner et al. 2020; Basri et al. 2022). BSFF increases soil total C, N, NH_4^+ and microbial soil respiration (Klammsteiner et al. 2020). Consequently, the frass can replace commercial fertiliser owing to its potential to recapture N and P from the food chain for reuse as a fertiliser (Schmitt and de Vries 2020). However, the NPK ratios of BSFFF are highly variable, subject to what the black soldier fly feeds on. According to Nicholson et al. (1996), the concentration of N, P and K in frass is the same as that found in farmyard manure and, particularly, poultry manure. Beesigamukama et al. (2020) noted that fertilising maize with BSFF increased maize N uptake by 76% and 29% compared to commercial organic fertiliser and urea respectively.

Agricultural soils in SSA are low in macronutrients and secondary nutrients (Wortmann et al. 2019) and there is a general lack of organic and inorganic replenishment (Jones et al. 2013). Soil fertility is the major limiting factor affecting yield increases (Pradhan et al. 2015). Incorporating BSFFF into the soil improves the fertility, WHC, the overall health and might also induce plant resistance to abiotic stresses (Poveda et al. 2019). BSFF has the ability to supply nutrients to plants and enhance plant growth similar to most commercial organic fertilisers or even better (Quilliam et al. 2020; Menino et al. 2021) because of high content range of N (0.6–4.8), P (0.8–2.5), and K (0.2–2.1) (Basri et al. 2022). Some researchers (Beesigamukama et al. 2020; Quilliam et al. 2020; Anyega et al. 2021) noted significant increase in crop yield, nutrient uptake, N use efficiency and disease tolerance following use of BSFFF.

Therefore, BSFFF promises to be a sustainable and innovative solution for amending marginal and degraded sub-Saharan soils. Its high nutrient content and appreciable amounts of organic matter make it a valuable resource. However, there is still need for more research to determine the applicability of this resource under various conditions and the possibilities of integrating this resource with other existing technologies and agricultural systems and practices. This chapter discusses the potential of BSFF as a potential transformative resource for revitalising marginal soils. The chapter also highlights nutrient content of BSFF and its impact on soil fertility, soil structure, soil biological properties, and seeks to provide a pathway towards the sustainable use of BSFF.

2 The Black Soldier Fly and Its Frass

2.1 Overview of the Life Cycle and Behaviour of the Black Soldier Fly

The life cycle of the BSF is 38–45 days, comprising of four phases, namely egg, larva, pupa, and adult stage (Fig. 1). The adults mate and then lay up to 500 eggs on a substrate close to an appropriate food source; for instance, compost organic waste, including manure (Zhou et al. 2013), food scraps (Nguyen et al. 2015) and municipal refuse (Amrul et al. 2022). The eggs take approximately 4.5 days (102–105 h) to hatch. The larvae feed constantly (between 25 mg and 500 mg) and their size differ

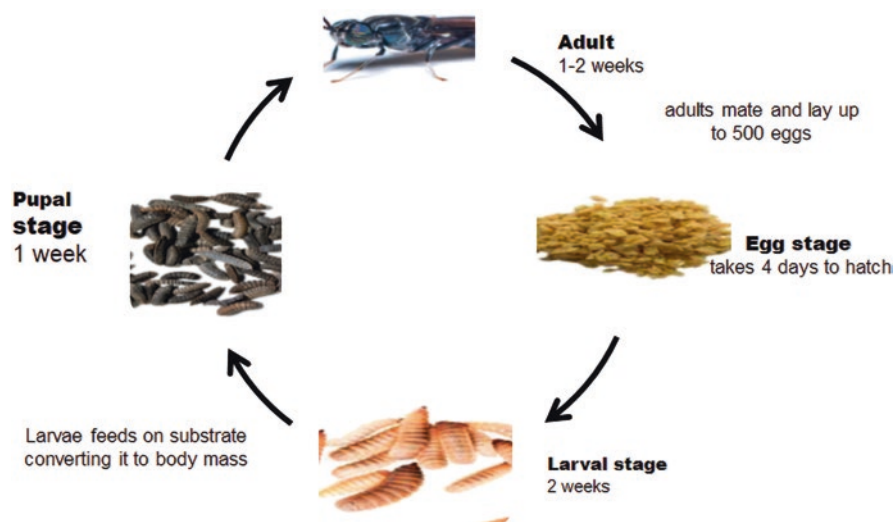


Fig. 1 Life cycle of black soldier fly (Adapted from Terfa 2021)

depending on what they eat, and environmental conditions such as temperature, light, and humidity (Makkar et al. 2014).

The larvae of BSF can consume most rotten/fermented organic material including decaying fruits, vegetable waste, animal manure, and municipal organic waste (Li et al. 2011), with their weight increasing up to 5000 times (Susanto et al. 2022). The larvae take about 2–3 weeks to reach the prepupal stage (Li et al. 2011). Consequently, a pupa develops from the inside of the exoskeleton. The adult develops from the pupa case, subsequently emerging to reproduce again and the cycle is repeated (Guilliet et al. 2022).

The adult BSF is approximately 15–20 mm long (Hardouin and Mahoux 2003) and is narrow, with a whitish colour (Diclaro II and Kaufman 2009). They are not robust flyers and hence they spend the greater part of their time resting on plants. The male and female BSF are different; the male has a bronze abdomen, whereas the female is reddish-brown (Kumar et al. 2018). The BSF rarely feeds when it has reached the adult stage since it lives on fat reserves that are accumulated during the larval stage. They tend not to transmit disease owing to their lack of stinging mouthparts (non-biting).

2.2 Description and Composition of Black Soldier Fly Frass

BSFF is a combination of BSF larvae excretion, uneaten substrates and shed exoskeletons (Amrul et al. 2022). BSFF is comprised of chitin, which is a by-product of the exoskeleton and acts as a plant activator and chemical inducer of disease resistance. Chitin also acts as a nematicide and fungicide, and promotes mycorrhization (Dzepe et al. 2022). BSFF is not a uniform product; the microbial, physical and chemical composition is highly dependent on the food source. For example, the composition of BSFF derived from chicken litter typically has approximately 23.6% C, 2.3% N, 1.1% P, and 1.8% K (Liu et al. 2019). Similarly, BSFF produced from various sources such as brewery spent grain (Beesigamukama et al. 2020), pig manure (Liu et al. 2019), household waste (Kawasaki et al. 2020), fresh soy pulp (Chiam et al. 2021), and commercial fertiliser (Beesigamukama et al. 2020) may exhibit variations in composition (Fig. 2). Additionally, factors like geographical location and post-processing methods have been shown to influence BSFF properties, as observed in studies by Lopes et al. (2020) and Anyega et al. (2021).

In a study conducted by Klammsteiner et al. (2020), BSFF produced from chicken feed, fruit and vegetable mix, and grass consumption exhibited distinct characteristics. The BSFF derived from CF was found to be more alkaline and had a higher electric conductivity compared to the other sources. However, the total C content was similar among all three types of BSFF. The C:N ratio for both chicken feed and grass consumption BSFF had relatively close values, with chicken feed at 18.5 and grass consumption at 18.2. In contrast, the BSFF produced from the fruit and vegetable mix had a noticeably higher C:N ratio of 26.6. In another study, BSFF produced from household waste contained both major elements N, P, K and trace

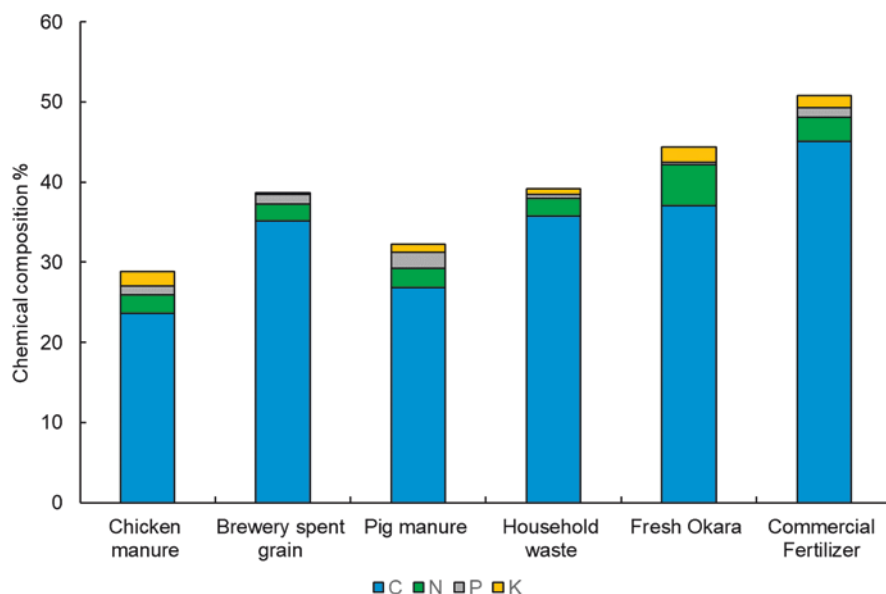


Fig. 2 The chemical composition of BSF frass in various feed substances (Adapted from Tran et al. 2022)

elements Ca and Mg (Dzepe et al. 2022). In addition, the BSFF had a high organic matter content (90%) and a high C:N ratio ranging between 25 and 35. Despite the differences in nutritional content, the effect on crop yield was similar (Devic 2016). These studies attest to the high nutrient compositions of BSFF, which can be used in improving soil with poor soil fertility.

2.3 The Process of Frass Production in Black Soldier Flies

There are four units needed for BSFF production, namely unit for rearing, waste treatment, harvesting and post treatment (Fig. 3). On the rearing unit, BSFs are kept in cases and they only need water to survive (Banks et al. 2014). Sufficient lighting and ventilation are essential to trigger mating. For mating to occur, relative humidity (60%) and temperatures ranging from 27.5° to 37.5 °C are required (Holmes 2010; Barragan-Fonseca et al. 2017). Oviposition ought to be central to avoid random egg laying. The eggs are then collected between slates. The nurtured larvae are then relocated to treatment units.

In waste treatment (processing), all harmful and inorganic substances ought to be removed from the substrate. Furthermore, the particle size of the substrate must be reduced (Boaru et al. 2019). This enables the BSF larvae to be able to digest the substrate, thereby promoting its growth. If the moisture content is too high (between 90% and 97.5%), it must be reduced (dewatered) because extreme moisture

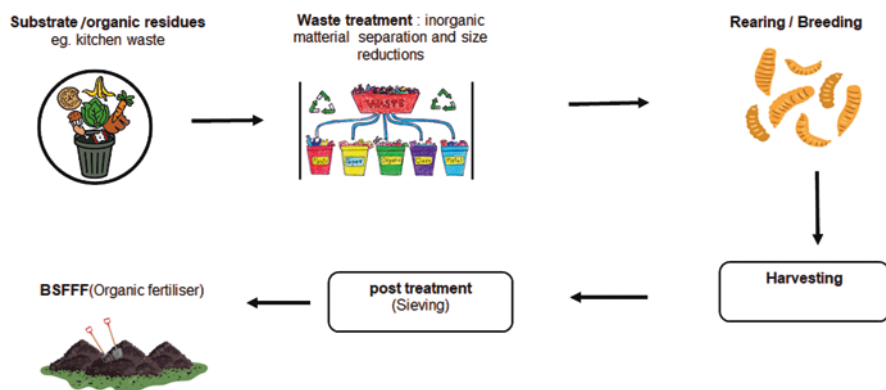


Fig. 3 The process of frass production in black soldier flies (Adapted from Peguero et al. 2022)

decreases the degradation rate of the substrate (Diener et al. 2011; Bekker et al. 2021). Adequate light ($135\text{--}200\ \mu\text{mol}/\text{m}^2$) and ventilation are also required during the rearing stage for mating to occur (Kim et al. 2021). The larvae and frass are then harvested. Thereafter post treatment commences where the larvae and frass are separated. The larvae will pupate and develop into adult BSFs whilst the frass will be sieved to remove pre-pupae (Myers et al. 2008) (Fig. 3).

3 The Science of Soil Reclamation Using Black Soldier Fly Frass

3.1 How Black Soldier Fly Frass Improves Soil Fertility and Structure

Black soldier fly frass has several soil health and fertility benefits. Research by Quilliam et al. (2020) showed that BSFF had pathogen suppressing qualities while Agustiyani et al. (2021) showed its capacity to increase soil microbial activities because BSFF serves as a food source for soil microorganisms. These microorganisms play a vital role in breaking down organic matter, releasing nutrients, and improving soil structure. Beesigamukama et al. (2022) observed improved N mineralisation through BSFF application, leading to increased nutrient availability and reduced soil salinity and acidity due to its buffering capacity. Bortolini et al. (2020) observed increased organic matter content following application of BSFF in intensely cultivated soils. This enhancement was attributed to BSFF's substantial C content, which not only ameliorates soil structure and water retention, but also contributes to higher total C and total N levels, as well as a heightened soil NH_4^+ pool (Klammsteiner et al. 2020; Elissen et al. 2023). The addition of organic matter to the soil enhances soil structure through improved aggregation, which creates larger

pore spaces that improve infiltration and root penetration. The improvement in infiltration and water holding capacity is particularly beneficial in marginal soils with limited water availability. Improved soil structure and aggregation also reduces susceptibility to wind and soil erosion. Moreover, BSFF contains microorganisms like nitrifying and nitrogen-fixing bacteria (Choi and Hassanzadeh 2019), fostering plant growth and bolstering N availability for plants, thus enhancing soil resilience against degradation. Furthermore, the significant N and P levels within BSFF are efficiently recaptured in the food chain, functioning as valuable fertiliser components (Schmitt and de Vries 2020). Additionally, the high cation exchange capacity of BSFF positions it as a promising slow-release organic fertiliser.

3.2 The Role of Frass in Restoring Soil Microbial Activity

One of the most significant benefits of BSFF application to soil is the improvement in soil microbial activity, diversity and biomass. Soil microbes play an essential role in soil structure formation, help in the breaking down of organic matter, provide nutrients and promote plant growth (Barrios 2007). Soil microbes cycle major nutrients such as N and P and play a major role in soil carbon sequestration. Consequently, when organic amendments like BSFF are added to the soil, they stimulate microbial activity and boost the functional potential of the microbial community (Houben et al. 2020).

Gebremikael et al. (2020) reported increased microbial biomass C and enzyme activities with application of frass. Frass application also increased the amount of net cumulative carbon mineralised and the simulated fraction of stable carbon. Similarly, Watson et al. (2021) reported significantly higher microbial biomass in BSFF amended soils relative to the non-amended control. However, the soil microbial composition found in soils amended with BSFF differs depending on the feed substrate supplied to the larvae (Wynants et al. 2019; Gold et al. 2020). Moreover, Gebremikael et al. (2020) noted that both microbes and chitin inherent to BSF larvae residues are main drivers of soil microbial diversity. BSFF has high chitin content, which fosters the growth of soil microbes rich in the enzymes required to break down root-knot nematodes. Therefore, it functions as a nematicide and fungicide, and promotes mycorrhisation (Quilliam et al. 2020; Watson et al. 2021). Application of BSFF results in more diverse soil micro-biome, which aids in converting N in its ammoniacal form to nitrate form, which permits for more effective root uptake by the plant enhancing plant growth and development (Terfa 2021). In addition, *Bacillus* and *Pseudomonas* bacteria will be in abundance, thereby helping fix atmospheric N (Boiocchi et al. 2017; Poveda et al. 2019; Gold et al. 2020).

3.3 *Impacts of Frass on Soil pH*

On average, BSFF has a neutral to alkaline pH of 7.46 (Meneguz et al. 2018; Gärtling and Schulz 2022). However, the pH values fluctuate between 5.4 to 9 and this is highly dependent on the properties of the feed source (Klammsteiner et al. 2020). Frass obtained from substrate derived from fruit and vegetables had a pH of 5.6 whilst a combination of chicken droppings, sawdust and maize straw (3:2:1 ratio) had a pH of 8.0 (Basri et al. 2022). The slightly acidic pH offers favourable conditions for improving soil biological properties (Choi and Hassanzadeh 2019) and promoting plant growth (Surendra et al. 2020).

4 Case Studies and Experimental Results Supporting Frass as a Tool for Soil Reclamation

4.1 *Successful Examples of Frass Usage in Africa's Marginal Soils*

Numerous successful applications of BSFF derived from various substrates have demonstrated its positive impact on enhancing soil properties and crop yields across Africa. For instance, a study conducted in Kenya by Terfa (2021) revealed that vegetables fertilised with BSFF exhibited N and P uptake comparable to plots treated with commercial organic and mineral fertiliser. Similarly, Beesigamukama et al. (2020) found that applying BSFF at a rate of 7.5 t/ha significantly boosted N uptake by up to 23% compared to an equivalent rate of commercial organic fertiliser (SAFI) for maize (H513) cultivation in Kenya. The authors further highlighted that BSFF not only enhanced N uptake, but also improved soil health by introducing organic matter and releasing vital nutrients to support maize production. Numerous other studies (Beesigamukama et al. 2020; Bortolini et al. 2020; Choi and Hassanzadeh 2019; Quilliam et al. 2020) highlighted the enhanced growth and yield of crops fertilised with BSFF. Additional African studies highlighting the application of BSFF are presented in Table 1.

The addition of organic matter is particularly beneficial to revitalisation efforts for marginal soils. The addition of organic matter plays a crucial role in improving soil structure, nutrient retention, and overall fertility and is therefore particularly beneficial to the rehabilitation efforts for marginal soils (Malobane et al. 2022). Organic matter serves as an energy source for soil microorganisms; therefore, the addition of sufficient amounts of organic matter builds a thriving microbial community, which in turn leads to improved soil aeration and nutrient cycling. Moreover, as soil microbes break down organic material, they release various enzymes and compounds that improve both nutrient solubilisation and availability to plants (Rashid et al. 2016).

Table 1 Effects of BSFF on soil quality and crop productivity

Authors	Location	Soil type	Substrate	Results
Beesigamukama et al. (2020)	Kenya	Shallow depths, low OM, and low pH levels	Brewery spent grains	BSFF performed better than commercial organic (SAFI) and inorganic fertilisers. Improved nitrogen use efficiency
Anyega et al. (2021)	Kenya	Acric Ferralsols-medium acidity, low levels of N, P, and OM	Brewery spent grains	BSFF boosts the growth, yield, and nutritional quality similarly or better than the commercial organic and mineral fertilisers
Tanga et al. (2022)	Kenya	Acric Ferralsol—Loamy, medium acidity, and low OM, TN, and P	Brewery spent grains	Sole use of or BSFF integration with mineral NPK fertiliser could be a solution for improved soil health
Dzepe et al. (2022)	Cameroon	Low clay and high sand content. Low C:N ratio, poor quality of OM	Organic waste	Desirable values for N, P ₂ O ₅ and K ₂ O
Boudabbous et al. (2023)	Tunisia	Mediterranean soil-clayey-loam, medium OM, medium pH, high available potassium, and K	Feeding substrate	BSFF reduced soil pH and EC but also led to higher nutrient content and soil microbial biomass carbon. BSFF performed better than cow manure
Abiya et al. (2022)	Kenya	Humic nitisols-sandy clay, and well-drained	Brewer's spent grains	BSFF had higher nitrogen and potassium concentrations. Performed better than inorganic fertiliser NPK
Agustiyani et al. (2021)	Indonesia	Ultisol soil	Garbage disposal	BSFF improved soil biochemical properties compared to compost and NPK
Menino et al. (2021)	Portugal	Haplic Fluvisol	Vegetable by-products	Significant increase in OM, K and P,

4.2 Comparisons of Black Soldier Fly Frass Fertiliser with Traditional Soil Remediation Methods

Black soldier fly frass fertiliser has a similar nutrient content to poultry manure and farmyard manure, with comparable concentrations of N, P and K (Table 2). Nicholson et al. (1996) and Gärttling and Schulz (2022) found that BSFF had a higher organic matter content than other manure and compost types. Elissen et al. (2023) found that the C:N ratio of BSFF was similar to cow slurry, while the K

Table 2 Nutritional components of different manure in frass (Adapted from Joshi et al. 2015 and Elissen et al. 2023)

Manure/compost	OM (g/kg)	N _{total} (g/kg)	N _{organic} (g/kg)	Phosphate (g/kg)	Potassium (g/kg)	C:N ratio
Pig slurry	738	65	31	36	44	12
Cow slurry	772	43	23	16	59	17
Poultry manure	740	51	46	41	34	8
Green compost	299	8	8	4	7	19
BSFF	844–886	34	–	27–28	25	13–16
Vermicompost	493–498	22–24	–	10	–	12
Farmyard manure	460–463	14	–	7	–	19

content was close to that of poultry manure. These findings therefore indicate that BSFF can be a viable and sustainable alternative to traditional manures, composts and fertilisers. Moreover, BSFF offers a sustainable option for waste valorisation since it can be produced from a using a variety of organic waste materials, including food scraps, manure, and agricultural by-products.

5 Practical Applications and Techniques

5.1 Methods of Applying Frass to Marginal Soils

There are different methods used for applying BSFF to soils, e.g., incorporation into soil, broadcasting on soil or topdressing. These methods depends on specific needs and circumstances. BSFF can be broadcasted evenly over the soil surface by hand or using mechanical spreaders. There are different methods used for applying BSFF to soils, e.g., incorporation into soil, broadcasting on soil or topdressing. These methods depend on specific needs and circumstances. BSFF can be broadcasted evenly over the soil surface by hand or using mechanical spreaders followed by discing to incorporate the fertiliser into the soil. This can also be done manually with a rake on small areas. BSFF can also be applied in furrows or between the rows for row crops. However, direct application onto the soil or composted as an organic fertiliser is the most common application method (Bulak et al. 2020). For instance, Beesigamukama et al. (2020) used the heap method to compost frass for 5 weeks. A mature stable product was produced and applied thereafter. In several instances, BSFF has been applied as a foliar fertiliser or used in hydroponic systems. Black soldier fly frass can also be used to irrigate plant after diluting with water.

Other applications methods include directly spreading on soil surface as much or possibly incorporating into mulch mats known as agrimats. Agrimats are a new technology that involves pressing waste biomass into a biodegradable mulch mat (Mgolozeli et al. 2020, 2023). Preliminary studies have shown that agrimats have

the potential to improve the productivity of marginal soils. Additionally, the incorporation of high-nutrient materials such as dry algae has shown positive results (Mgolozeli et al. 2023). A similar approach could be used by embedding BSFF in agrimats, which would allow for a slow release of nutrients over time. The eventual decomposition of the mat will add organic matter to the soil hence improving soil structure and other related properties.

5.2 Considerations for Integrating Frass Application into Existing Agricultural Practices

Some researchers, i.e., Tiftonell et al. (2008), Vanlauwe et al. (2015), Musyoka et al. (2017) suggested that mixing of mineral and organic fertilisers can improve nutrient use efficiency, soil fertility and crop yields. Similarly, Malobane et al. (2022) summarised findings on impacts of integrating livestock manure and inorganic fertiliser on crop yields under rainfed conditions in sub-Saharan Africa. Most of the studies reviewed showed more benefits of combined application of organic and inorganic fertilisers compared to sole application. Similarly, Wakindiki et al. (2019) noted the integration of biofertilisers into conservation agricultural systems and other climate smart agricultural practices has the potential to build up soil organic carbon (SOC) stock and reduce greenhouse gases emissions compared to the use of inorganic fertilisers alone. In addition to supplying nutrients to plants, organic nutrient sources also improve soil microbial communities, which in turn contributes to improved soil structural properties. This is particularly important for the rehabilitation of marginal soils.

Another potential consideration is the application of BSFF and biochar mixtures to marginal soils. Nyambo et al. (2023) outlined the benefits of biochar use in degraded soils due to the following biochar properties: high internal surface area, high ratios of recalcitrant carbon, increased micro-nutrient bio-availability and reduced bio-availability of heavy metals. Biochar provides high inputs of recalcitrant carbon, which enhances carbon sequestration by preventing the loss of SOC back to the atmosphere as carbon dioxide. Moreover, biochar also improves the availability of nutrients and water. Therefore, combining BSFF and biochar can potentially offer several benefits to the properties of marginal soils. For instance, biochar provides a recalcitrant form of organic carbon, which can persist for a long time in the soil. Its combination with BSFF, which also has high amounts of organic carbon, can contribute to increased soil organic matter in the soil. Similarly, biochar is widely known for its ability to improve soil fertility by increasing nutrient retention and availability while BSFF is rich in nutrients like NPK. Consequently, when combined the two organic amendments can work synergistically to enrich marginal soils with essential nutrients. Since biochar has water retention properties, its combination with BSFF can further enhance moisture retention, hence improving the productivity of marginal soils. Lastly, the utilisation of both BSFF and biochar can

contribute to sustainable waste management, which promotes circular economy principles and reduces waste generation.

6 Cost-Effectiveness of Using Black Soldier Fly Frass for Soil Reclamation

6.1 Potential Challenges and Solutions

Production of BSFF involves specialised equipment such as rearing facilities, waste management systems, and processing equipment, which might be expensive for smallholder farmers. In addition, specialised knowledge is required, which can be a challenge to most smallholder farmers in sub-Saharan Africa. However, smallholder farmers can possibly overcome this challenge by creating cooperatives in which they share the cost of the equipment and in turn share the facilities. Despite solving the prior challenges, BSFF is still a new concept and might be faced with resistance, hence the need for awareness seminars. For the frass to be of good quality, high quality substrates should be used and collecting it in huge quantities might be a challenge in the long run. Collaborating with food processors that produce organic waste can be a worthwhile solution.

6.2 Addressing Potential Health Risks and Ecological Impact

Adult black soldier flies hardly move because they rely on the food reserves they accumulated during their larval stage. Moreover, they do not have a stinger therefore; they cannot pass any diseases that affect humans (Ji-bin et al. 2020; Rehman et al. 2022). In addition, black soldier fly larvae excrete infochemicals that deter other species of flies, reduce pathogenic bacteria, and deter insect pests and disease vectors. This makes them a potential biocontrol agent for houseflies. (Erickson et al. 2004; Diener et al. 2011; Shumo et al. 2019). However, the application of frass in large concentrations results in yield reduction (Temple et al. 2013) and growth inhibition (Alattar et al. 2016) due to ammonium toxicity. Therefore, there is need to mix it with other types of organic compost or fertiliser. There is also need for more research aimed at identifying the most suitable application rates of BSFF.

7 Conclusions and Future Directions

7.1 Recap of the Potential of Black Soldier Fly Frass in Revitalising Africa's Marginal Soils

There is significant potential for revitalising Africa's marginal soil with BSFF. Since it is organic in nature, BSFF is high in organic matter and essential nutrients such as NPK as well as beneficial microorganisms. These components are crucial in enhancing the fertility, structure and water retention of marginal soils. Moreover, BSFF provides a sustainable option for waste valorisation through resource efficient solutions, which in turn offers a pathway towards enhancing food security and agricultural sustainability in the face of marginal soil conditions.

Whilst there is sufficient scientific evidence on the potential of BSFF to sustainably rehabilitate marginal soils, there is need for policies that advocate for the inclusion of BSFF in soil management strategies. There is need for increased awareness of the benefits of this organic nutrient source as well as policies that promote further research and development leading to the establishment of quality standards and waste management practices.

7.2 Potential Research Areas to Further Explore the Effectiveness of Frass

There are several gaps in knowledge on the use of frass that still need to be addressed in Africa. For instance, BSFF is still new in Africa; there is still need for studies on the long-term effects of BSFF on soil properties and carbon sequestration. The majority of findings currently available are from short-term glasshouse studies. Long-term field studies will shed more light on the sustainability of the technology, especially its potential for soil carbon sequestration. There is also need to explore potential effects of BSFF on microbial community dynamics and elucidate the possible interactions between BSFF, soil microbes and nutrient cycling processes. Research on crop specific responses to BSFF application and site-specific soil management is also imperative as it can enable the establishment of practices tailor-made for marginal soils. Moreover, these study areas can also be applied to a combination of BSFF and biochar. It will be particularly important to determine appropriate mixtures of the amendments and the effects thereof.

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Vermicomposting for Improved Soil Health: Prospects for Degraded Soils



M. A. Manyanga, J. Marumure, N. Chigede, M. Mubvuma, C. P. Mudzengi, I. Nyambiya, and M. Muteveri

1 Introduction

Soil degradation is a common challenge impacting crop production in SSA. It can be in form of physical degradation through loss of soil or Some of the causes of soil degradation includes monoculture which lead to nutrient mining (Jones et al. 2013) limited use of inorganic fertilizers (Cobo et al. 2010), soil erosion. Growing same type of crop and adopting same farming practices can result in soil fertility decline due to excessive pressure on land (Rahman and Ranamukhaarachchi 2003). Depletion of soil organic matter (SOM) degrades ecosystem services and loses ecosystem resilience. Continuous use of inorganic fertilizers can cause serious soil health problems such as soil acidity and environmental pollution. Place et al. (2003) noted that southern Africa has the lowest fertilizer use among smallholder farming systems compared to the rest of the world which is of great concern given that soils in most parts of SSA are said to be infertile. Low crop yields in Kenya and Tanzania have been attributed to low soil fertility (Keino et al. 2015). Some soils in South Africa have very low K and P lowering their potential for cultivation (Buhmann

M. A. Manyanga (✉) · M. Mubvuma

Department of Soil and Plant Sciences, Gary Magadzire School of Agriculture, Great Zimbabwe University, Masvingo, Zimbabwe

J. Marumure

Department of Physics, Geography and Environmental Sciences, School of Natural Sciences, Great Zimbabwe University, Masvingo, Zimbabwe

N. Chigede · C. P. Mudzengi

Department of Livestock, Wildlife and Fisheries, Gary Magadzire School of Agriculture, Great Zimbabwe University, Masvingo, Zimbabwe

I. Nyambiya · M. Muteveri

Department of Mathematics, Statistics and Computer Sciences, School of Natural Sciences, Great Zimbabwe University, Masvingo, Zimbabwe

et al. 2006). In Zimbabwe, most communal soils are sandy derived from granite rock with very low water and nutrient retention capacity making them very susceptible to nutrient leaching and erosion. All these result in decreased soil health, thereby reducing the soil's ability to sustain crop growth leading to low yields. A healthy soil has balanced physio-chemical properties and has the ability to maintain good plant growth through supplying required amount of plant nutrients in adequate amounts at the right time.

Maintaining good soil health is important for sustainable agriculture. Conservation agriculture, for example, has been promoted for improving soil physical, chemical, and biological qualities, but its success remains low with farmers still experiencing soil fertility decline and other related problems. Given the soil health problems farmers still face, they are highly encouraged to convert to organic farming (Yadav et al. 2013). Vermicompost provides a great opportunity for improving soil health thereby reducing soil degradation. Vermicomposting is a biological process that uses a variety of worms, including earthworms, to convert organic waste into nutrient-rich natural compost through the interaction of worms and microbes (Rahman and Barmon 2019).

The resultant vermicompost (Dominguez and Gomez-Brandon 2013) have been found to improve soil properties (Basheer and Agrawal 2013). Vermicompost improves soil fertility and plant growth in degraded soils, minimizing the detrimental effects of low soil organic matter (SOM) (Doan et al. 2015). SOM provides a number of advantages, including a balanced supply of nutrients, greater soil nutrient availability due to increased soil microbial activity, breakdown of hazardous components, improved soil structure, and improved soil water availability (Han et al. 2016). Most notably, vermicompost aids in the restoration of soil stability after toxicity (Gutierrez-Miceli et al. 2008). As a result, implementing sustainable agriculture techniques aids crop output while preserving soil quality, increasing soil organic matter, and protecting the environment (Rahman and Barmon 2019). This helps in the rehabilitation of degraded soils as well as reducing the rate of soil degradation. This take us to the research questions: (1) Will vermicompost use help improve soil physical, chemical and biological properties? (2) Is vermicompost use the way to go for improved crop production? Thus, the main objective of this literature synthesis is to ascertain the benefits of using vermicompost in improving soil health. The specific objectives are to: (a) identify how vermicompost use influences soil physical, chemical and biological properties (b) evaluate the benefits of vermicompost use in improving crop production.

1.1 Vermicomposting Process

Vermicomposting adheres to the fundamentals of the circular bio-economy, where organic wastes are bio-converted and reused in crop production to accomplish sustainable agriculture (Ratnasari et al. 2023). The process involves the biotransformation or decomposition of organic waste using earthworms and microorganisms like

bacteria and fungi to generate a product that is rich in plant nutrients, a biofertiliser also known as vermicompost (Marumure et al. 2023). During the same process the earthworm biomass is significantly increased (Ramos et al. 2022). The main architects of biotransformation during the vermicomposting process are the earthworm species, *Eisenia fetida* since they are easy to find on soil surfaces and can survive in any environment. However, the majority of earthworm species are capable of vermicomposting (Ratnasari et al. 2023). More importantly, compared to other living organisms, earthworms are frequently recommended for vermicomposting because of their high tolerance for a variety of environmental conditions, such as different soil acidity level (Ratnasari et al. 2023).

The biotransformation mechanisms responsible for converting organic wastes into vermicompost during the vermicomposting are documented in studies by (Marumure et al. 2023). Generally, processes linked to the mechanisms occur within the gut of earthworms and include biodegradation of solid organic wastes, enzyme synthesis and enrichment (Ahmad et al. 2021). According to Marumure et al. (2023), the earthworm stomach serves as a bioreactor in which a variety of enzymes are secreted to promote the digestion of organic waste. Proteases, phosphatases, amylase, and mucin are just a few of the numerous enzymes that make up the earthworm digestive system (Ratnasari et al. 2023) and play a role in the digestion process. Furthermore, earthworm gut microflora are central in the bioconversion of all organic vermicompost substrates. Proteobacteria, Bacteroidetes, Verruca, and Actinobacteria were discovered to be the main bacteria in vermicomposts (Huang et al. 2023). More importantly, it has been demonstrated that the bacteria speed up the mineralization of organic matter and enhance the production of nutrients during vermicomposting (Zhou et al. 2022). Notably, nitrogen fixing bacteria (e.g., *Rhizobium*, *Mesorhizobium*, *Bradyrhizobium*, and *Azospirillum*), nitrifying bacteria (e.g., *Nitrosomonas*, *Nitrosospora*, *Nitrosococcus*, and *Nitrospira*), and phosphorus-solubilizing bacteria (e.g., *Acinetobacter*, *Flavobacterium*, *Pseudomonas*, and *Streptomyces*) were all discovered in a number of vermicomposts (Huang et al. 2023).

Through enrichment with other well-known organic wastes, several studies have shown that organic wastes can be vermicomposted quickly and effectively (Badhwar and Singh 2021). According to Badhwar et al. (2020), the quantities of cow manure added increased earthworm growth and the ability to reproduce. This in turn enhanced the vermicomposting process. Similar conclusions were drawn from vermicomposting of a mixture of sludge from the bakery industry and cow dung (Yadav and Garg 2019). A successful vermiconversion, for instance, produced vermicompost with improved nutrients from paper mill sludge, tea wastes, and cow manure. Studies have also shown that vermicomposting reduces the accessible proportion of several metals and metalloids, including arsenic (As), copper (Cu), cadmium (Cd), chromium (Cr), nickel (Ni), lead (Pb), and zinc (Zn), regardless of the earthworm species or kind of raw material employed (Goswami et al. 2016; Lv et al. 2016; He et al. 2016).

1.2 *Why Vermicomposting?*

Crop production is a source of livelihoods for many people especially in Sub Saharan Africa. Unfortunately, most of the soils have been repeatedly cropped without much soil fertility amendments being added leading to soil degradation in the form of poor fertility as well as increased susceptibility to erosion. Other soils are inherently infertile because of the geology from which they were derived for example granite derived soils are usually acidic and low in nutrients. As such yields on such soils have been low with most farmers yielding way below optimum levels. In Zimbabwe, maize yields have been consistently below 1 t/ha for most communal farmers who are the majority. To make matters worse, many farmers do not use any soil fertility amendment due to either high costs of inorganic fertilizers or its untimely availability as well unavailability of organic resources. Interestingly, a lot of organic waste is produced in the form of household waste and crop residues among other waste and all this can be vermicomposted. The fact that vermicomposting can be done in structures such wooden and brick boxes which can be of varying sizes depending on amount of organic residue available for processing means it can be customized for use at different scales from small to large scale. Also, high costs of organic fertilizers, and little to unavailability of often poor-quality organic resources make it very important for farmers to look for alternative sources of nutrient rich soil amendment in the form of vermicompost. Given all the benefits of vermicompost in improving soil physical, chemical and biological properties, it is a very cost-effective way of improving soil health and can be used to amend degraded soils resulting in increased crop production and food security.

1.3 *Vermicomposting as a Sustainable Practice*

Use of inorganic resources have been promoted as a way of supplying crops with required nutrients for increased crop production. However, inorganic sources of nutrients are susceptible to leaching and with some finding their way into water bodies more often causing eutrophication. This increase the costs of fertilizers required to balance the crop nutrient requirement which many farmers with fertility degraded soils cannot afford. Also, inorganic resources have minimum direct benefits to improving especially soil physical and chemical properties. As such there is need to use a resource that improve soil health that is enhancing soil physical, chemical and biological properties such as vermicompost. Unlike use of chemical fertilizers which causes environmental pollution if done un-judiciary, vermicomposting is an eco-friendly approach thus sustainably promotes life in the soil and the surrounding environment through supporting plant life. Vermicompost balance underground soil environment and makes it a suitable habitat for soil microbiota through its vermicast which is rich in hormones and enzymes favourable for soil microbiota. Microbes are the fundamental elements of the ecosystem. Use of vermicompost

which is basically from organic waste improves crop growth and multiplication of microbes that improves environment's betterment in a sustainable way.

Sustainability is a concept of utilizing the natural resources without compromising the ability of future generation to meet their own needs. Therefore, vermicompost can be used to sustainably utilize soil resources through maintaining its productive capacity thereby reducing chances of soil degradation. Vermicompost is a sustainable product for managing degraded soils since it is mainly produced from organic waste which in itself is waste recycling. Its use on soils result in slow release of nutrients reducing chances of nutrient leaching thereby lowering chances of off-site pollution especially of water resources.

1.4 Benefits of Vermicomposting on Marginal Soils

Most marginal soils are often low in macro, meso and micro nutrients, have low water holding capacity and poor structure among other problems which negatively impact on their production potential. To address these problems, farmers can use vermicompost which is a cost-effective organic fertilizer. Application of vermicompost can have a positive effect since it contains various plant nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, manganese, zinc, copper, and boron that improve the nutrient content of plants (Tammam et al. 2023). Przemieniecki et al. (2020) highlighted the following significant increases in soil nutrient content carbon/nitrogen ratio from 21 to 32, as well as the content of nitrate from 78 to 134 mg kg⁻¹, ammonium from 14 to 139 mg kg⁻¹, phosphorus from 92 to 521 mg kg⁻¹, and of potassium from 142 to 1912 mg kg⁻¹ following vermicompost application highlighting its potential in improving fertility of marginal soils. Most importantly these nutrients will be in available form for plant uptake. Since it is an organic fertilizer, vermicompost has potential to alleviate the negative effects of salinity on saline soils improving its ability to sustain plant growth.

Most degraded soils especially those with high sand fractions have poor soil structure and low water holding capacity. Incorporation of vermicompost on such soils can improve aggregation and aggregate stability in the process reducing bulky density, increasing porosity, infiltration and subsequently water retention. Soils with better aggregation are less susceptible to erosion which is critical in maintaining its chemical and physical stability and the general soil health. Vermicompost is a sustainable way of improving soil health since it improves its microbial activity, physical and chemical properties without having an effect on the environment.

1.5 Benefits of Vermicompost on Soil Biological Properties

Vermicomposts have far greater and more diversified microbial communities than traditional composts (Edwards 1998). The population of plant-growth-promoting rhizobacteria grows as a result of earthworm activities (Sinha et al. 2010). This is because they ingest rhizospheric bacteria that include *Pseudomonas*, *Rhizobium*, *Bacillus*, *Azospirillum*, and *Azotobacter* and together with rhizospheric soil and the ideal micro-environment of their gut, activate these bacteria (Pathma and Sakthivel 2012). Adhikary (2012) noted that earthworms excreta products are fertile organic fertilizers, with high levels of humus, stable organic matter, macro and micronutrients, diverse beneficial soil microorganisms, and growth hormones. Vermicomposting alters the microbial populations of waste in a variety of ways which is beneficial to soil biological properties. Vermicompost, for example, had high levels of Actinobacteria and Gammaproteobacteria, whereas traditional compost had higher levels of Alphaproteobacteria and Bacteroidetes, which are bacterial phylogenetic groupings present in non-cured compost (Vivas et al. 2009).

Singleton et al. (2003), posits that earthworms have ‘nitrogen-fixing’ and ‘decomposer microbes’ in their gut, which they excrete along with nutrients in their castings. Therefore, use of vermicompost increases populations of nitrogen fixing bacteria in the soil. Nitrogen fixing bacteria are very important especially when they are in contact with roots of a nitrogen fixing leguminous plant. The resulting biological nitrogen fixation (BNF) is important for improving soil fertility because it allows the plant to acquire nitrogen, which is often the most limiting nutrient for plant growth. Vermicompost is an organic material which is also a good source of food for soil microbes like bacteria and fungi. Therefore, its application to degraded soils can improve microbial diversity from microfauna to macrofauna with microfauna being critical in mineralization making nutrients available for plant uptake potentially improving the soil fertility status of soil. Macrofauna like earthworms and termites burrow in soil in the process increasing infiltration.

1.6 Effects of Vermicompost Use on Soil Physical Properties

Vermicompost is rich organic matter which is finely divided peat-like material with high porosity and water holding capacity (Olle 2019). Several studies have found that adding vermicompost to soil improves its physical properties significantly (Chatterjee et al. 2020; Demir 2019; Akhzari et al. 2015), with the higher application rates of vermicompost having the greatest effect on soil physical properties (Aksakal et al. 2016) which is important for degraded soil. Some of the soil physical properties improved by vermicompost include aeration, moisture content, reduced bulk density, water holding capacity, porosity, corrosion resistance, and penetration resistance (Aksakal et al. 2016). The organic matter in vermicompost helps improve all these soil parameters due to its beneficial properties such as increasing

aggregation and water absorbance among other benefits which will be important in improving productivity potential of degraded soils. Vermicompost has also been reported to improve physical properties in salt affected soils (Ibrahim et al. 2015).

Increase in soil porosity is important in improving water infiltration and air circulation in the soil (Chaudhari et al. 2013), hence enhancing soil's ability to sustain plant growth. Worm castings, in reality, contain a higher proportion of humus, which aids in the creation of soil aggregates and formation of pore spaces thereby increasing soil's water-holding capacity (Adhikary 2012). Vermicomposit increase wet aggregate stability, decreased dispersion ratio of soils in different aggregate size fractions, and decreased penetration resistance (Aksakal et al. 2016). Suhane et al. (2008) indicated that vermicompost can retain more soil moisture thereby lowering irrigation water requirement by about 30–40%. In SSA about 18% of soils are susceptible to leaching (Sanchez et al. 2003) which presents an opportunity for using vermicompost on soils with such physical problems. This clearly shows that using vermicompost is an effective way to improve soil physical characteristics, thereby promoting crop production (Aksakal et al. 2016). Some of the benefits of vermicompost to physical properties are presented in Table 1.

1.7 Managing Soil Fertility Through Using Vermicompost

In tropical Africa, about 3 billion hectares of land is arable, yet only half of it is free of chemical and physical concerns, with low nutrient content in 13% (Ugboh and Ulebor 2011). Sanchez et al. (2003), asserts that about 40% of soils in SSA have poor nutrient capital stocks, meaning they have less than 10% weatherable minerals, and 25% suffer from aluminum toxicity, with high leaching potential in 18% of the area. Low soil fertility is hurting the productivity of numerous agricultural systems in many parts of southern Africa (Cobo et al. 2010). Therefore, application of vermicompost will be critical in increasing soil organic matter content thereby ensuring sustainable nutrient release during mineralization for enhanced crop productivity.

Vermicompost is an excellent manure rich in many essential nutrients required by crops such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and micronutrients that is iron (Fe), zinc (Zn), copper (Cu) and manganese (Mn) in sufficient amounts to boost crop productivity and quality (Kumar et al. 2018). Humic acid in humus offers these plant nutrients with binding sites (Kumar et al. 2018). This is very important since low cation exchange capacity is a problem in many degraded soils especially those which are sandy. Most importantly, these nutrients are stored in the humic acid in a form that is readily available to the plants and are released when they are needed (Adhikary 2012). Findings by Uz et al. (2016) showed that vermicompost appeared to be more effective than farmyard manure at increasing organic matter, N, P, and Ca. Azarmi et al. (2008) discovered that applying sheep dung vermicompost at a rate of 15 t ha⁻¹ resulted in soils with higher total organic carbon (TOC), N, P, K, Ca, Zn, and Mn than soils that did not

Table 1 Effects of vermicompost use on soil physical properties

Soil physical property	Vermicompost effects	Remarks	Reference
Water holding capacity (%)	Increased from 43 + 0.01 to 47 + 1.0	Presence of organic matter results in water retained to nourish crops and keep soil organic matter alive	Atkinson (2018)
Porosity (%)	Increased from 36 + 1.0 to 41 + 1.0	Crucial for conducting water, air, and nutrients into the soil, which is needed for plant growth.	Indoria et al. (2017)
Moisture content (%)	Increased from 39 + 1.1 to 44 + 1.0	Controls the structure, ductility, and density, temperature and heat of the soil. Water in the large and intermediate size pores can move about in the soil and be easily used by plants.	Schoonover and Crim (2015)
Wet aggregate stability (%)	Increased from 26.9 to 52.2	More pore space is provided for water to enter, resulting in an increase in soil water holding capacity. Good aggregate stability also aids root development, allowing the plant to absorb more water and nutrients.	Aksakal et al. (2016), Schoonover and Crim (2015) and Brevik (2010)
Soil bulk density	Reduced	Pore space expands, resulting in increased available water capacity, root growth, and air and water movement through soil.	Aktaş and Yüksel (2020)
Air permeability (μ^2)	Increased from 90.7 ± 10.9 to 133.5 ± 3.3	Allows air and water to flow freely through the soil, which is critical because it affects the amount of root-zone air, moisture, and nutrients available for plant uptake.	Aksakal et al. (2016) and Ball (2001)
Soil dispersion ratio (fractions, mm) (%)	Reduced from 46.4 ± 2.0 to 30.1 ± 2.3	Forms a good stable soil structure	Aksakal et al. (2016)
Penetration resistance (kg cm^{-2})	Reduced from 2.88 ± 0.09 to 1.18 ± 0.08	Indicates soil strength, allowing crop root growth, and is also critical in the design and selection of agricultural machinery	Aksakal et al. (2016) and Jiang et al. (2020)

get vermicompost. The presence of N_2 fixers and phosphate solubilizing bacteria increases the availability of macronutrients like N and P to plants (Chitrapriya et al. 2013). Because phosphate is one of the most limited and least transportable nutrient, the presence of phosphate-solubilizing bacteria is critical for phosphate supply. Application of vermicompost also enhance soil organic carbon status (Mahewarappa et al. 1999) (Table 2).

Earthworm activity during the vermicomposting process help reduce pH and C:N ratio in the manure (Atiyeh et al. 2000). The application of vermicompost to soil was found to lower soil pH levels (Azarmi et al. 2008). This can be very important in rehabilitation of problem soils such as saline soils which have higher pH values. Management of such problem soils is critical because a significant

Table 2 Organic carbon content of ordinary soil compared to vermicompost

Nutrient	Earthworm castings/ vermicompost	Ordinary top soil	Reference
Organic carbon content	48.2 (g/kg)	11.9 (g/kg)	Khang (1994)
	15%	1.07%	Azarmi et al. (2008)
	181 ± 3 (g/kg)	31 ± 1 (g/kg)	Adhikary (2012)

proportion of land has salinity problems making crop production very difficult. The use of vermicompost in a reclaimed sodic soil lowered the soil's sodicity in just 12 weeks, according to studies (Ansari 2008). These findings show that vermicompost presents a great opportunity for managing and or rehabilitating some of the degraded soils.

1.8 Crops Response to Vermicompost Application

Little to no use of soil amendments especially organic material has led to constant soil degradation especially from a fertility point resulting in reduced crop production which calls for the need to use nutrient rich material such as vermicompost. Beneficial roles of vermicompost start from seedling production with some results showing the positive effect of vermicompost on germination and early growth of seedlings (Lazcano et al. 2010). Application of vermicompost soot to horticultural crops has been found to improve growth and yields as well as suppress pests and diseases. Arancon et al. (2019) noted that tomato yields significantly increased following application of vermicompost teas. Vermicompost was found to contain a combination of trace plant hormones (auxins, cytokinins, gibberellins and humic acids in vermicomposts teas) which were attributed to increased lettuce and tomato yields (Arancon et al. 2019). Other studies demonstrate the importance of vermicompost in crop growth and yield in cereals Benik and Bejbaruah (2004), as well as in fruits Glenda et al. (2009). Vermicompost can be used in crops as a basal organic fertilizer at planting and its soot as a top dressing fertilizer. The positive effects of vermicompost to different crops can be attributed to its ability to improves physical, chemical and biological properties. For example, improved soil physical qualities have been connected to improved root growth conditions (Lim et al. 2015) which possibly contribute to greater plant growth and productivity (Durak et al. 2017). A 178.7 g plant⁻¹ increase in lettuce yields was observed in soil treated with 5% vermicompost (Demir 2019). The higher content of nutrients such N, P, K, Ca, Cu, Mg, Fe, and Zn discovered in vermicompost compared to farmyard manure resulted in greater garlic (*Allium sativum*) growth and output (Suthar and Singh 2008). Given these and other benefits to crop production, vermicompost presence a good chance of improving crop production on degraded soils Thus, the technology has potential

to address the need for high plant growth and cost-effective land reclamation and restoration.

1.9 Conclusion

Vermicompost is a sustainable organic product which can be used in managing degraded soils which are often characterized by low nutrient content and poor water holding capacity especially in SSA. Its use has several benefits which include improving soil aggregation, structure, water holding capacity, infiltration, microbial activity nutrient supply subsequently leading to increased crop production. Also, given the negative effects of climate variability especially the effects of mid-season droughts and leaching due to flush floods, using vermicompost can help in soil moisture conservation as well as reducing nutrient loss through leaching since nutrients will be released slowly. For sustainable management of soil properties, vermicompost can be utilized either singly or in an integrated approach together with other sources of nutrients. The major advantage of vermicompost is it can be used as basal fertilizer and its soot as top-dressing folia fertilizer which is a cost-effective way of improving soil fertility of degraded soils. Vermicompost production should be promoted especially in communal areas where farmers can properly heap grass during weeding as well as harvest grass from field edges and vermicompost it. Cattle manure from free grazing system found in most rural areas is often of poor quality and vermicomposting such manure can significantly improve its nutrient content. Resource constrained farmers can pull their resources together and collectively set up vermicomposting structures which can be key in them producing nutrient rich organic resource. Vermicompost is an important organic resource which can be key in managing degraded soil through improving its physical, chemical and biological properties leading to improved crop production on such degraded soils.

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Reclamation Technologies for Marginal Soils in Africa: Strategies, Challenges, and Future Directions



Collin L. Yobe and Binganidzo Muchara

1 Introduction

The degradation of soil resources is a pressing issue affecting agricultural productivity and ecosystem health in various regions worldwide (Rengasamy 2006; Hossain et al. 2020). Africa faces significant challenges related to soil degradation, adversely affecting food security, rural livelihoods, and environmental sustainability (Wegenast and Beck 2020; Wang 2022). Marginal soils, characterised by their low fertility, poor structure, and limited water-holding capacity, are widespread in many parts of Africa and exacerbate the problem of soil degradation (Lal and Stewart 2019).

This chapter aims to shed light on reclamation technologies tailored explicitly for African marginal soils. The main goal is to explore practical methods to improve these damaged soils' fertility and functionality to support resilient ecosystems and sustainable agricultural growth. This chapter offers valuable insights for policymakers, land managers, academics, and stakeholders involved in soil reclamation activities by exploring the various reclamation methods available and their possible uses in African contexts.

Soil deterioration significantly impacts agricultural productivity, which lowers crop yields and farmer revenue (Shah et al. 2021). Degraded soils make people more vulnerable to climate change because they cannot survive intense weather and store carbon (Balasundram et al. 2023). Additionally, soil fertility loss impacts ecosystems' health, including water quality and biodiversity. (Lehmann et al. 2020). To ensure sustainable agricultural practices, food security, and environmental preservation in Africa, executing effective reclamation solutions for marginal soils is essential.

C. L. Yobe (✉) · B. Muchara

University of South Africa, Graduate School of Business Leadership, Midrand, South Africa

This chapter has two goals to achieve. The chapter's first goal is to give readers a thorough understanding of the traits and causes that contribute to the deterioration of African marginal soils. Understanding the particular difficulties and limitations different soils experience helps to know how hard the reclamation process is. Second, this chapter explores various reclamation strategies appropriate for African marginal soils. The chapter will explore successful projects that have recovered damaged soils through case studies and examples, highlighting the guiding principles of each technique and their potential applications in the African setting.

The following is how the chapter will accomplish these goals. It will start by looking at the characteristics and causes of the degradation of marginal soils in Africa. This section will thoroughly explain the difficulties encountered in soil reclamation initiatives. The chapter will then give an overview of several reclamation procedures, including physical, chemical, and biological methods, that are employed for marginal soils. The chapter can evaluate these technologies' effectiveness and applicability in African settings by examining their principles and applications.

The chapter will include case studies highlighting effective African reclamation initiatives to show how reclamation technologies are used in real-world applications. These case studies will emphasise technological uses, particular circumstances, and results. The chapter can learn important lessons for future reclamation activities by analysing these success stories to determine the elements that contributed to their efficacy.

For reclamation technologies to be effective over the long term, their effectiveness must be evaluated. In light of the significance of long-term monitoring and adaptive management strategies, the chapter will explore the methodology and indicators used to evaluate the effectiveness of various technologies. The difficulties and restrictions in implementing reclamation technology in African contexts, including socioeconomic, environmental, and institutional constraints, will also be identified. By acknowledging these difficulties, solutions can be developed to help reclamation operations succeed.

The chapter will assemble best practices for choosing and implementing reclamation technologies based on the knowledge learned from the earlier sections. The chapter will gather best practices for selecting and implementing reclamation technologies based on the knowledge learned from the earlier areas. These best practices will consider factors such as cost-effectiveness, scalability, and sustainability, providing practical guidance for policymakers, land managers, and stakeholders in Africa's soil reclamation efforts.

Furthermore, the chapter will discuss emerging trends and innovations in reclamation technologies, highlighting areas that require further research and exploration. The future directions and research needs identified in this chapter will emphasise the importance of interdisciplinary collaboration and knowledge sharing to advance the field of these reclamation technologies to suit the specific conditions and limitations of African marginal soils, optimise their effectiveness, and ensure sustainable outcomes.

2 Understanding Marginal Soils in Africa

Marginal soils refer to those with limited fertility and poor physical and chemical properties, making them less suitable for sustainable agricultural production (Lal and Stewart 2019). These characteristics of the soils are low organic matter content, inadequate nutrient levels, poor water-holding capacity, and often possess a high degree of acidity or alkalinity. Typically, they are found in arid and semi-arid regions and areas with steep slopes, shallow depths, or high erosion rates. Marginal soils may also occur in the areas affected by mining activities or pollution.

Several factors contribute to the degradation of marginal soils in Africa. One significant factor is improper land management practices, including unsustainable agricultural practices such as overgrazing, excessive tillage, and inadequate soil erosion control measures (Shinde et al. 2019). These practices can lead to soil erosion, nutrient depletion, and soil compaction, exacerbating the degradation of already marginal soils.

Climate variability and change also play a role in soil degradation. Increasing temperatures, erratic rainfall patterns, and prolonged droughts in some areas of Africa contribute to soil moisture stress, reduced organic matter decomposition, and increased soil erosion rates (Rao et al. 2023). These climatic factors further degrade marginal soils' already limited fertility and water-holding capacity, making them even more unsuitable for agricultural production.

Population pressure and the expansion of agricultural activities are additional factors driving soil degradation in marginal areas (Maja and Ayano 2021). As the population grows, the demand for food and resources increases, leading to the conversion of marginal lands for agricultural purposes. Without proper land management practices, this expansion can exacerbate soil degradation, as marginal soils are more susceptible to the negative impacts of intensive farming systems.

The impacts of degraded soils on agricultural productivity and ecosystem health are profound. Lower fertility and nutrient availability in degraded marginal soils in agriculture lead to lower crop yields and agricultural output. Farmers who depend on these soils struggle to meet their demands for food and revenue, which feeds the cycle of poverty and food insecurity (Hossain et al. 2020; Lal and Stewart 2019; Rao et al. 2023; Reij and Garrity 2016).

Degraded soils in remote regions can provide environmental problems. Topsoil and vital nutrients are lost due to soil erosion, a frequent result of soil degradation (Hossain et al. 2020, Lal and Stewart 2019, Rao et al. 2023, Reij and Garrity 2016). Additionally, the eroded sediments may have a detrimental effect on water bodies, causing water contamination and the decline of aquatic habitats (Coffey et al. 2019). Degraded soils also have a lower water-holding capacity, which raises the possibility of runoff and water scarcity during dry spells. Reduced biodiversity and fewer ecosystem services are two factors that further worsen ecosystems' vulnerability.

Degraded soils also have a lower water-holding capacity, which raises the possibility of runoff and water scarcity during dry spells. Reduced biodiversity and fewer ecosystem services are two factors that further worsen ecosystems'

vulnerability (Hoffmann et al. 2022). Local communities' income and well-being are impacted by the loss of productive agricultural land and lower crop yields, contributing to poverty and reducing prospects for economic development.

Effective reclamation solutions are needed to address the issues with marginal soils in Africa. Reclamation activities aim to improve soil health, increase water retention, and restore soil fertility. It is possible to restore degraded marginal soils and increase agricultural production by implementing sustainable land management strategies, including agroforestry, conservation agriculture, and soil erosion control measures.

In conclusion, it is essential to comprehend the characteristics and causes of soil deterioration in Africa's remote places to create successful reclamation solutions. Due to the effects of degraded soils on agricultural output, rural livelihoods, and ecosystem health, rapid action is essential to remediate damaged soils and promote sustainable land management practices. In Africa, improving the fertility and functionality of marginal soils by applying suitable reclamation methods can help with food security, the reduction of poverty, and environmental sustainability.

3 Overview of Reclamation Technologies

Implementing diverse reclamation technologies designed to address their unique characteristics and problems is necessary to restore African marginal soils. These methods include physical, chemical, and biological ones, each with guiding principles and possible uses in African settings. Enhancing the physical properties of marginal soils is the primary goal of physical reclamation technologies (Qureshi et al. 2023; Hussain et al. 2020). These techniques seek to improve soil structure, water retention, and erosion control. Soil mulching, which involves covering the soil's surface with organic materials like straw or crop leftovers, is one often used approach. Mulching enhances moisture retention, regulates soil temperature, and lessens evaporation. This approach is beneficial in arid and semi-arid areas where water is challenging. Furthermore, contour ploughing and terracing prevent soil erosion by lowering runoff and increasing water infiltration, making them useful on steep slopes.

Chemical reclamation technologies apply additions or inputs to increase the availability of nutrients and soil fertility (Diatta et al. 2020; Hafez et al. 2021). In many marginal soils, liming is a popular procedure to treat soil acidity. Applying lime to the ground helps to raise its pH, which lowers the toxicity of manganese and aluminium and increases the availability of vital minerals. Another chemical strategy to restore nitrogen levels in deficient soils is fertiliser application. The suitable types and amounts of fertilisers are essential for achieving the best outcomes, and soil testing and analysis are crucial steps in this process. To prevent nutrient imbalances and environmental damage, utilising fertilisers wisely and in moderation is essential.

Utilising the strength of soil microbes and plants to restore the health and functionality of the soil is the primary goal of biological reclamation methods (Coban et al. 2022). The application of cover crops or green manures is a crucial biological strategy. These are crops that are cultivated more for soil enhancement than for harvest. Cover crops improve soil organic matter, reduce erosion, fix atmospheric nitrogen, and replenish nutrient levels. Leguminous plants can create symbiotic relationships with microbes that fix nitrogen; growing them can also increase soil fertility. The basics of these reclamation techniques must be adapted for African settings to consider marginal soils' unique constraints and requirements. For instance, technologies concentrating on water conservation and effective irrigation systems become crucial in arid and semi-arid regions where water availability is restricted. Methods like terracing and drip irrigation can be paired with rainwater gathering and physical reclamation techniques to maximise water consumption and encourage soil moisture retention.

Similar to this, in locations where soil acidity is a significant problem, the application of lime can be customised to the unique requirements of the soil, taking into account elements including the degree of acidity, the soil's ability to act as a buffer, and the accessibility of local supplies of lime. Additionally, adding organic amendments to the ground, such as compost or manure, can improve the soil's structure, nutrient retention, and microbial activity, increasing the efficiency of chemical reclamation techniques. Local sourcing of these organic materials can cut prices and advance sustainable agricultural methods.

Biological reclamation technologies can be utilised in Africa by choosing cover crops and green manures well-suited to the local climate, soil types, and cropping methods. Local leguminous species can be discovered and used for crop rotations to increase nitrogen fixation and soil fertility. Additionally, encouraging agroforestry systems, which plant trees alongside crops, has several advantages, including improved soil structure, more significant organic matter input, and higher biodiversity. In conclusion, physical, chemical, and biological techniques are needed to reclaim African marginal soils. These innovations improve soil health generally, restore soil fertility, and improve water retention in marginal soils.

4 Case Studies of Reclamation Technologies in Africa

This section will give case studies illustrating effective African reclamation initiatives, showcasing the various technologies and their results. These case studies offer important insights into the elements that contributed to the success of these activities, serving as a guide and source of inspiration for upcoming reclamation initiatives.

4.1 Case Study 1: Farmer-Managed Natural Regeneration in Niger

The Farmer-Managed Natural Regeneration (FMNR) technique has been crucial in repairing degraded soils and fostering sustainable land management practices in Niger, a country in West Africa known for its extensive drylands (Rinaudo 2007; Francis et al. 2015; Mustapha 2021). FMNR entails the selective regeneration and management of woody vegetation that grows naturally on farms, such as shrubs and trees. This method generally enhances soil fertility, moisture retention, and ecosystem health (Reij and Garrity 2016; Rinaudo 2007).

Identifying and preserving naturally regenerating trees and bushes in their fields, Nigeran farmers have adopted FMNR (Rinaudo 2007, Francis et al. 2015, Mustapha 2021). Farmers that actively manage these vegetation resources have seen improvements in soil organic matter, water penetration, and biodiversity. In addition to lowering moisture loss, the regenerated plant's shade helps regulate soil temperature.

Several factors contributed to FMNR's success in Niger. First and foremost, involving and empowering local farmers in managing natural resources is essential. Farmers are best positioned to determine which tree species are most suited for their particular agroecological circumstances since they thoroughly understand their land. Additionally, by combining FMNR with agricultural techniques like mulching and agroforestry systems, the benefits of soil restoration and agricultural productivity are maximised (Francis et al. 2015; Mustapha 2021; Reij and Garrity 2016; Rinaudo 2007).

4.2 Case Study 2: Conservation Agriculture in Zambia

In Zambia, adopting conservation agriculture techniques has shown promising results in reclaiming degraded soils and improving agricultural productivity (Thierfelder et al. 2013; Baudron et al. 2007). Conservation agriculture combines three critical practices: minimal soil disturbance (no or reduced tillage), permanent soil cover (mulching or cover cropping), and crop rotation. These techniques enhance soil structure, water-holding capacity, and nitrogen cycling.

To lessen soil disturbance, farmers in Zambia have adopted conservation agriculture by implementing minimum tillage techniques such as employing direct seeders or ripper ploughs (Baudron et al. 2007). This strategy promotes water infiltration, reduces erosion, and preserves soil structure. Crop wastes, such as mulch or cover crops, can create permanent soil coverage. These techniques enhance the organic matter content of the soil, prevent erosion, and encourage healthy soil microbes. Crop rotation is also used to break pest and disease cycles, diversify cropping systems, improve soil fertility, and lessen dependency on chemical inputs.

In Zambia, conservation agriculture has produced notable results. Farmers who practice conservation agriculture have reported better water availability, fewer soil

erosion problems, and higher crop yields. Adopting these techniques has also improved indices of soil health, such as raised soil organic matter levels and increased microbial activity (Baudron et al. 2007; Thierfelder et al. 2013).

Numerous variables have contributed to conservation agriculture's success in Zambia. The promotion and adoption of these methods have mainly depended on farmer training and capacity-building initiatives (Corbeels et al. 2014). Extension services, non-governmental organisations, and research facilities have been instrumental in supplying technical assistance, promoting knowledge exchange, and highlighting the advantages of conservation agriculture (Lwoga et al. 2010). Additionally, suitable machinery, such as direct seeders and rippers, have made minimal tillage practices possible, making conservation agriculture more accessible to farmers (Baudron et al. 2007).

4.3 Case Study 3: Integrated Soil Fertility Management in Ethiopia

Improved agricultural output and the restoration of degraded soils have been demonstrated benefits of using Integrated Soil Fertility Management (ISFM) practices in Ethiopia (Hörner and Wollni 2021; Agegnehu and Amede 2017). Based on soil testing, ISFM blends organic inputs like compost or manure with the appropriate application of mineral fertilisers. This strategy increases agricultural yields, nutrient availability, and soil fertility.

Ethiopian farmers have used organic inputs like compost or manure in ISFM. These organic inputs help to maintain soil structure, encourage nutrient retention, and support microbial activity. Farmers have increasingly embraced site-specific nutrient management based on soil testing to ensure targeted and efficient fertiliser application. This approach minimises the environmental risks posed by the overuse of fertilisers while optimising nutrient use.

The outcomes of the application of ISFM in Ethiopia have been positive. Better crop yields, more rich soil, and increased food security have been reported by farmers who adopt ISFM (Garritty et al. 2010). By utilising locally accessible organic inputs and maximising fertiliser application, farmers have increased their subsistence and maintained their soils sustainably.

Several things contributed to ISFM's success in Ethiopia. Programs for farmer education and training have been essential in encouraging the use of ISFM practices (Takahashi et al. 2020). Giving farmers the knowledge and abilities to implement ISFM successfully has been crucial to its success. Farmers' decisions about nutrient management have also been greatly influenced by their access to reputable soil testing services and agronomic counsel. Furthermore, programs supporting resource recycling and sustainable waste management have made accessing organic inputs like compost and manure easier.

These case studies demonstrate different reclamation techniques and how well they work in African settings. The key components that make these efforts successful are farmers' active participation, local knowledge and abilities, capacity-building programs, the availability of the appropriate tools and inputs, and supportive laws and institutions. Understanding and utilising these factors will enable future reclamation attempts to be effectively designed.

The case studies in this chapter's conclusion show how important reclamation technologies are for restoring African marginal soils. Physical, chemical, and biological techniques have increased agricultural output, ecosystem health, and soil fertility. When choosing and putting into practice reclamation technologies, it is necessary to consider the site-specific characteristics and constraints of marginal soils and socioeconomic and environmental considerations.

Policymakers, land managers, researchers, and stakeholders must work together to develop and implement context-specific strategies to achieve sustainable soil management and agricultural development in Africa. These strategies must integrate traditional knowledge with scientific advancements, promote knowledge sharing and capacity building, and provide support through policies, funding, and technical assistance. The chapter can continue to encourage reclamation technology and ensure that African soil restoration initiatives are successful over the long term by investing in research, innovation, and interdisciplinary collaboration. Reclamation technologies that work are essential for guaranteeing food security, reducing climate change, and enhancing the standard of living for millions of people across the continent.

5 Assessing Efficacy: Evaluation and Monitoring

It is essential to assess the success of reclamation methods for marginal soils to ascertain their performance, pinpoint areas for development, and direct future implementation plans. Monitoring and evaluation offer essential insights into how various technologies work, how they affect soil restoration, and how they support sustainable agriculture practices. This section will cover the significance of measuring efficacy, assessment methods, indicators, and approaches to long-term monitoring and adaptive management.

5.1 Importance of Evaluating Efficacy

Allocating resources and making decisions based on evidence are made possible by evaluating the effectiveness of reclamation technology. It enables all parties involved, including politicians, land managers, and researchers, to comprehend the results and efficacy of various strategies and to choose which technologies to prioritise and scale up. The evaluation also contributes to creating sustainable and

affordable treatments by offering insights into the costs and advantages of various reclamation strategies on the economic, social, and environmental fronts.

5.2 Methodologies and Indicators for Assessing Effectiveness

The efficiency of reclamation technologies for marginal soils is evaluated using a variety of methodologies and indicators. These consist of field observations, laboratory analyses, participatory assessments, and quantitative and qualitative methods.

1. **Soil physicochemical analysis:** This entails assessing the soil's structure, organic matter content, pH level, and level of nutrients. These indicators can be compared before and after the use of reclamation technologies to learn more about changes in soil fertility, nutrient availability, and physical characteristics (Xu et al. 2023; Ezeokoli et al. 2020).
2. **Crop performance assessment:** The effectiveness of reclamation systems can be determined by monitoring plant growth, crop output, and health. When assessing the productivity and quality of crops grown on reclaimed soils, comparisons with baseline data or control plots are available, highlighting improvements in agricultural production. (Gondek et al. 2020).
3. **Water management assessment:** Analysing water usage effectiveness, soil moisture retention, and water infiltration rates will help you comprehend how reclamation methods affect the availability and management of water. This assessment is particularly relevant to dry or semi-dry areas where a restriction is a lack of water (Zheng et al. 2023).
4. **Erosion control monitoring:** By assessing soil erosion rates and contrasting them with pre-intervention levels, erosion management systems' efficacy can be ascertained. Use sediment trapping, erosion pins, or aerial surveys to determine erosion rates (Al-Mamari et al. 2023).
5. **Biodiversity and ecosystem health assessment:** It is possible to assess the ecological effects of reclamation methods by observing changes in biodiversity, such as the abundance of helpful insects, soil bacteria, and vegetation cover. The long-term sustainability of recovered soils can be determined by evaluating the return of native species and the creation of healthy ecosystems (Kumar et al. 2022; Lupardus et al. 2021).
6. **Socioeconomic assessments:** Assessing variables, including changes in farmer income, livelihood security, and social well-being, is necessary to evaluate the socioeconomic effects of reclamation technology. In-depth qualitative information about the advantages and difficulties of restoration operations can be obtained through surveys, interviews, and participatory methods (Uddin et al. 2020).

5.3 Long-Term Monitoring and Adaptive Management

Understanding reclamation technology's long-term effects and effectiveness requires long-term monitoring (Hu et al. 2021). It allows for identifying trends, patterns, and potential limitations that may emerge in the years following implementation. Long-term monitoring also facilitates adaptive management, wherein adjustments to reclamation strategies can be made based on evolving knowledge and changing environmental conditions.

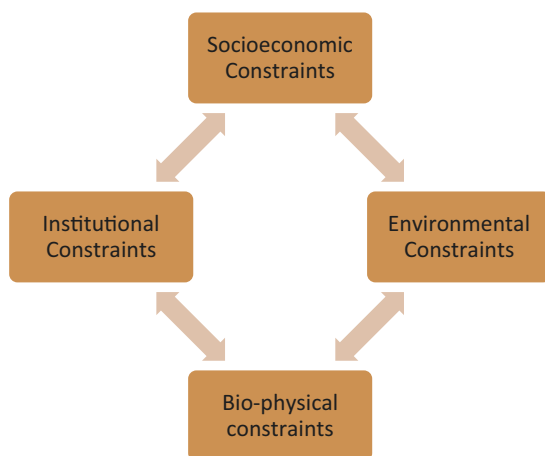
To improve reclamation strategies, adaptive management constantly learns from monitoring data, research findings, and stakeholder feedback (Littles et al. 2022). It allows for incorporating new knowledge and innovations into existing strategies, ensuring that interventions remain relevant and practical. Adaptive management approaches promote flexibility, responsiveness, and resilience in uncertain and changing conditions.

Continuous data collection, analysis, and stakeholder interaction are necessary for long-term monitoring and adaptive management. Cooperation between researchers, land managers, and local communities is essential for continual monitoring efforts and adaptive decision-making processes.

6 Factors Affecting Efficiency and Adoption of Soil Reclamation Technologies

There are difficulties and restrictions in applying reclamation technology for marginal soils in African environments. Socioeconomic, environmental, bio-physical and institutional factors (Fig. 1), affect the efficiency and successful adoption of these technologies. This section will outline some of the difficulties surrounding the

Fig. 1 Dimensions affecting social reclamation techniques (Source: Authors' illustration)



application of reclamation technologies in Africa, summarised in four broad themes (Fig. 1).

6.1 Socioeconomic Constraints

- *Access to resources:* Smallholder farmers in Africa frequently require assistance getting access to crucial resources, such as enhanced seeds, fertilisers, irrigation systems, and machinery, for putting reclamation technology into practice. Their capacity to invest in these technologies may be constrained by insufficient financial capital, financing facilities, and insufficient market connections (Bryan and Garner 2022).
- *Limited knowledge and awareness:* Many farmers might require more information about the potential advantages of reclamation technologies or need to learn about using them successfully. More education, outreach programs, and information sharing can promote the use and spread of these technologies (Bhattacharyya et al. 2021).
- *Land tenure and fragmentation:* The adoption and long-term deployment of reclamation methods might need to be improved by insecure land tenure regimes, land fragmentation, and disputes over land ownership. If farmers lack certain rights to the property or if their plots are too small to warrant the cost, they could be hesitant to make improvements (Shirzad et al. 2022).

6.2 Environmental Constraints

- *Water scarcity and variability:* Water scarcity and fluctuation are commonplace in many African regions, which presents substantial difficulties for reclamation techniques that depend on sufficient water for irrigation or soil restoration. Particularly in arid and semi-arid areas, limited access to water resources may limit the efficacy and scalability of these systems (Kama et al. 2023).
- *Climate change and variability:* Climate change impacts, including increased temperatures, changes in rainfall patterns, and extreme weather events, can affect the success of reclamation technologies. Unpredictable climatic conditions can lead to uncertainties in water availability, crop performance, and overall ecosystem dynamics, making implementing and sustaining reclamation efforts challenging (Tsakiris and Loucks 2023).

6.3 *Bio-Physical Constraints*

- *Soil heterogeneity and diversity:* Marginal soils in Africa exhibit considerable heterogeneity and diversity in terms of their properties, nutrient deficiencies, and degradation levels. Developing reclamation strategies suitable for different soil types and contexts can be complex, requiring site-specific approaches and tailored interventions (Regassa et al. [2023](#)).

6.4 *Institutional Constraints*

- *Lack of policy support and coordination:* Clear policies, guidelines, and regulations that support the adoption and implementation of reclamation technologies can help their widespread adoption. Weak coordination among government agencies, research institutions, and non-governmental organisations can lead to fragmented efforts and limited impact.
- *Limited infrastructure and extension services:* Inadequate infrastructure, including roads, storage facilities, and market access, can impede the adoption of reclamation technologies. Insufficient extension services, which provide technical advice and training to farmers, limit the dissemination of knowledge and the adoption of best practices (Muchuru and Nhamo [2019](#)).
- *Lack of research and innovation:* The limited availability of research and innovation tailored to local contexts and needs can hamper the development and refining of effective reclamation technologies. Insufficient investment in research, limited collaboration between researchers and practitioners, and a lack of knowledge-sharing platforms can hinder progress in this field.

7 **Strategies to Overcome Use and Adoption of Reclamation Technologies**

Thinking about a technology's cost-effectiveness, scalability, and long-term sustainability is crucial. Considering the financial gains, environmental effects, and social outcomes, technologies should yield a profit. Larger-scale replication and application of scalable technology can benefit more farmers and landscapes. Technology should also be sustainable, improving soil health, protecting natural resources, and having little adverse environmental effects. Policymakers, land managers, and stakeholders can design successful interventions, make informed decisions, and contribute to the sustainable reclamation of African marginal soils by adhering to some of best interventions (Fig. [2](#)).

Fig. 2 Strategies to overcome use and adoption of soil reclamation technologies (Source: Authors' illustration)



1. *Strengthening access to resources:* Efforts should be made to improve smallholder farmers' access to essential resources for implementing reclamation technologies; this can include providing affordable credit facilities, establishing input supply chains, promoting farmer cooperatives, and supporting the development of local markets for agricultural inputs.
2. *Enhancing knowledge and capacity building:* Investments in farmer training, extension services, and information dissemination are essential to improve farmers' knowledge and awareness of reclamation technologies. Training programs should focus on practical implementation techniques, emphasise sustainable land management practices, and incorporate local knowledge and indigenous practices.
3. *Improving land tenure and governance:* Addressing land tenure issues through implementing secure land rights and reducing land fragmentation can incentivise farmers to invest in land improvements. Strengthening land governance and resolving land conflicts through transparent and inclusive processes can provide a conducive environment for reclamation efforts.
4. *Adopting water-efficient technologies:* In regions with water scarcity, water-efficient irrigation technologies, such as drip irrigation and rainwater harvesting, can mitigate the challenges of limited water resources. These technologies promote efficient water use and reduce dependency on rainfall.
5. *Climate-resilient practices:* Implementing climate-resilient reclamation technologies that can withstand changing climatic conditions is crucial; this includes selecting crop varieties adapted to local climates, integrating climate-smart agriculture practices, and incorporating risk management strategies into reclamation projects.

6. *Site-specific and participatory approaches*: Tailoring reclamation strategies to the specific characteristics of marginal soils and involving local communities in decision-making is crucial to overcoming environmental constraints. Participatory approaches promote community ownership and increase the likelihood of technology adoption.
7. *Policy support and coordination*: Advocating for policies that support reclamation efforts and enhance coordination among government agencies, research institutions, and NGOs is essential. Engaging with policymakers to create an enabling environment for adopting reclamation technology can drive successful interventions' scaling up.
8. *Investing in infrastructure and extension services*: Infrastructure development, including improving rural roads, storage facilities, and market access, can enhance the feasibility of implementing reclamation technologies. Expanding extension services and ensuring the timely delivery of technical support to farmers is critical for knowledge dissemination and adoption.
9. *Promoting research and innovation*: Increased investment in research and innovation tailored to local needs can lead to the development of more effective reclamation technologies. Encouraging collaboration between researchers, practitioners, and farmers and establishing knowledge-sharing platforms can facilitate the exchange of best practices and innovative solutions.

In conclusion, a diverse strategy is needed to address the difficulties and constraints of applying reclamation technology to African marginal soils. Enhancing knowledge and capacity, adopting water-efficient and climate-resilient practices, addressing land tenure issues, fostering participatory and site-specific approaches, arguing for supportive policies, investing in infrastructure and extension services, and encouraging research and innovation should all be part of the strategies. Stakeholders can unleash the potential of reclamation technology to improve soil health, agricultural production, and environmental sustainability in Africa by proactively and fully addressing these concerns.

8 Best Practices and Recommendations

Cost-effectiveness, scalability, and sustainability are just a few variables that require careful consideration when choosing and implementing reclamation technologies for marginal soils. The section compiles best practices for selecting and deploying reclamation technologies. Additionally, the chapter will offer suggestions for decision-makers, landowners, and others involved in soil reclamation initiatives.

1. *Site-specific approach*: Utilise a site-specific strategy while choosing reclaiming technology. To ensure the selected technologies are appropriate and efficient in the particular context, consider the regional soil characteristics, agroecological circumstances, and socioeconomic aspects.

2. **Participatory approach:** Involve stakeholders, like farmers and communities, in selecting and implementing reclamation technologies. To ensure the technologies suit their requirements and culture, involve them in decision-making processes, knowledge sharing, and capacity-building activities.
3. **Integrated approach:** Adopt an integrated strategy that includes several methods for reclamation to address the various soil limitations and degradation concerns. The effectiveness and durability of soil reclamation initiatives can be improved by combining physical, chemical, and biological approaches.
4. **Sustainable land management practices:** Along with the use of reclamation technologies, emphasise the adoption of sustainable land management techniques. Promote organic farming, conservation agriculture, and agroforestry to safeguard biodiversity, soil health, and water resources.
5. **Monitoring and evaluation:** Establish reliable procedures for monitoring and evaluating the performance and effects of reclamation technology. To track progress, spot obstacles, and make wise decisions, keep an eye on indicators of soil health, crop performance, water availability, and socioeconomic aspects regularly.
6. **Knowledge sharing and capacity building:** Encourage parties involved in soil reclamation to share knowledge and develop their capacities. Encourage the development of forums to exchange best practices, stories, and insights. To improve knowledge and skills, strengthen extension services, training programs, and farmer-to-farmer interactions.

9 Recommendations for Policymakers, Land Managers, and Stakeholders

1. **Policy support:** Develop and implement policies that encourage the use and expansion of reclamation technologies. Encourage farmers to invest in sustainable land management by offering incentives, subsidies, and favourable regulations. In order to create helpful and cogent policy frameworks, government agencies should better coordinate their efforts.
2. **Research and innovation:** Invest heavily in innovative research projects and technology for recovering marginal soils. Support research organisations, academic institutions, and collaborative efforts to create context-specific solutions, enhance current technologies, and investigate novel ideas. To close the gap between research and execution, encourage cooperation between academics, professionals, and farmers.
3. **Capacity building and extension services:** Enhance extension and capacity-building initiatives to offer farmers technical assistance, education, and consulting. To aid in the spread of reclamation technology, improve the abilities and knowledge of extension personnel and support farmer-led extension strategies.

4. Financial support and market access: Provide financial support mechanisms, such as credit facilities, grants, or subsidies, to enable smallholder farmers to invest in reclamation technologies. Improve market access for agricultural produce, ensuring farmers have fair prices and reliable product markets.
5. Collaboration and partnerships: Encourage cooperation and collaboration between the various parties involved in soil reclamation operations. Promoting cross-sectoral collaboration between the public and corporate sectors, NGOs, farmer groups, and academic institutes. Collaboration can increase the effectiveness and sustainability of reclamation programs by leveraging resources, experience, and information.
6. Scaling up and replication: Develop strategies for expanding practical reclamation efforts. Find scaling-up bottlenecks and obstacles, then research creative ways to get around them. Encourage the dissemination of effective models and procedures worldwide, promoting knowledge transfer and context-specific adaptation.

10 Future Directions and Research Needs

African marginal soil reclamation technologies are constantly changing due to breakthroughs, growing trends, and the demand for sustainable land management techniques. In addition to highlighting the value of interdisciplinary cooperation and knowledge exchange, this part will examine the prospects of reclamation technologies and identify research gaps and opportunities for additional investigation.

10.1 Emerging Trends and Innovations

1. Climate-smart reclamation technologies: Reclamation methods that are resilient and adaptable to shifting climatic circumstances are becoming more and more necessary as the effects of climate change worsen. The main emphasis of future studies is to develop climate-smart strategies that consider water availability, temperature extremes, and altered precipitation patterns.
2. Precision agriculture and digital technologies: Optimising resource utilisation and enhancing the effectiveness of reclamation technologies are both substantial potential benefits of integrating digital technologies with precision agriculture. Remote sensing, GIS (Geographic Information System), and data analytics are examples of innovations that can provide real-time information on the health of the soil, nutrient deficits, and crop performance, allowing for focused treatments and precise management techniques.
3. Biochar and soil amendments: Biochar, a carbon-rich material produced from biomass, has shown promise in improving soil fertility, water retention, and carbon sequestration. Further research is needed to explore the potential of biochar

and other soil amendments in enhancing the effectiveness of reclamation technologies, particularly in addressing nutrient deficiencies and improving soil structure.

4. Agroecological approaches: Integrating ecological concepts into agricultural systems is a critical component of agroecological techniques. Future studies should concentrate on creating methods for reclamation that resemble natural ecosystems, encourage biodiversity, improve soil health, and employ as few outside inputs as possible. Agroecological techniques, including agroforestry, cover crops, and crop rotation systems, are a few examples of how they can help with long-term soil reclamation.

10.2 Research Gaps and Areas for Further Exploration

1. Long-term impacts and sustainability: Long-term studies are required to evaluate the long-term impacts of reclamation methods on soil health, crop productivity, and ecosystem services. The long-term performance of these technologies should be monitored, as should the dynamics of soil degradation and recovery and the elements that contribute to long-term sustainability.
2. Socioeconomic impacts and equity: Understanding the socioeconomic effects of reclamation technologies, mainly on smallholder farmers and marginalised populations, is just as vital as determining their effectiveness. Research should examine the implications of using these technologies for equity, social acceptance, and economic viability. It should look into the social dynamics and gender implications of the adoption and advantages of reclamation activities.
3. Policy and institutional frameworks: Further research is required to determine how institutional and policy frameworks influence the adoption and expansion of reclamation technology. The effectiveness of current policies should be evaluated, as well as any obstacles to their implementation, and policy interventions that support sustainable soil reclamation should be suggested. Additionally, the study should concentrate on comprehending the institutional arrangements and governance frameworks supporting successful reclamation initiatives' implementation and coordination.

10.3 Interdisciplinary Collaboration and Knowledge Sharing

Interdisciplinary collaboration and knowledge sharing are crucial for tackling the difficulties and complexities of reclamation technologies. Crossing disciplinary, institutional, and geographic borders is important for collaboration and knowledge sharing among researchers, practitioners, policymakers, farmers, and locals. To create comprehensive strategies for soil reclamation, interdisciplinary research teams

can combine expertise from soil science, agronomy, ecology, social sciences, economics, and policy studies.

Additionally, knowledge-sharing platforms, such as conferences, workshops, and online forums, should be established to facilitate the exchange of experiences, best practices, and lessons learned. These platforms can promote collaboration, foster innovation, and create networks of stakeholders involved in soil reclamation efforts.

Additionally, research institutions, governmental bodies, and non-governmental organisations should prioritise capacity-building projects that improve the abilities and expertise of people involved in soil reclamation; this includes training courses, technical seminars, and farmer-to-farmer knowledge-transfer activities that enable local communities to participate in and contribute to long-term soil reclamation projects.

Finally, it should be noted that more work must be done on reclamation methods for African marginal soils. This work should concentrate on new developments, fill knowledge gaps, and foster interdisciplinary cooperation. The analysis can advance knowledge of and use of efficient and sustainable reclamation technologies, enhancing soil health, agricultural productivity, and ecosystem resilience. This is accomplished by embracing innovative approaches, conducting lengthy studies, and involving various stakeholders.

11 Conclusion

The effectiveness of reclamation systems for marginal soils in Africa was examined in this chapter. It began with comprehending the traits of marginal soils and the elements causing soil degradation in these regions. The study highlighted the urgent need for efficient reclamation solutions and examined the negative effects of degraded soils on agricultural output and ecosystem health. The overview of technologies for reclamation gave information on several methods, including physical, chemical, and biological ones. Each strategy's fundamental concepts and potential uses in African situations were examined. The chapter emphasised the significance of using a multi-technology integrated approach to address the numerous soil limits and degradation concerns. The chapter provided case studies of successful African reclamation projects, highlighting the real results that may be obtained using the right technologies. These case studies emphasised the value of context-specific approaches and the requirement to consider regional soil features, agroecological circumstances, and socioeconomic issues when developing reclamation strategies. These programs were successful because of the active community involvement, capacity building, and adaptive management techniques. The importance of assessing the effectiveness of reclamation technologies was also emphasised in this chapter. The importance of long-term monitoring and adaptive management was covered in the chapter, along with the methodology and indicators used to evaluate the efficacy of various technologies. Make informed judgments to enhance reclamation

plans by routinely tracking progress, recognising obstacles, and tracking soil health indicators, crop performance, and socioeconomic factors. However, there are difficulties in applying reclamation technology in African settings. The economic, environmental, and institutional barriers that may prevent the successful application of these technologies were outlined in this chapter. Significant obstacles include restricted access to financial resources, a lack of technical expertise, and inadequate policy and governance frameworks. The chapter examined various approaches that could be used to overcome these difficulties, such as multi-stakeholder engagement, capacity building, and policy assistance. The chapter produced a list of recommendations and best practices for choosing and implementing reclamation technology. These activities emphasised the significance of a site-specific approach, participatory decision-making procedures, integrated approaches, sustainable land management practices, monitoring and evaluation, knowledge sharing, and capacity building. In order to direct their actions, policymakers, land managers, and stakeholders received advice on supportive legislation, investments in research, capacity building, and collaboration. The chapter included new developments in reclamation technology as well as developing trends. These movements included promoting agroecological methods, biochar and soil additives, precision agriculture and digital technology integration, and climate-smart methods. The chapter also recommended areas for further research, such as socioeconomic ramifications, the function of institutional and policy frameworks, long-term effects and sustainability, and research gaps. This chapter's conclusion emphasises the significance of efficient reclamation technology for marginal soils in Africa. These soils' degradation seriously hampers food security, ecological sustainability, and agricultural production. However, there is much potential to restore soil health, increase agricultural output, and foster ecosystem resilience by implementing the right reclamation technology and sustainable land management practices.

With the correct mix of technologies, community involvement, and adaptive management, effective reclamation operations are demonstrated by the case studies provided in this chapter. Addressing the difficulties and constraints associated with putting reclamation methods into practice, removing obstacles, and establishing favourable conditions for sustainable soil management. The development of reclamation technologies will depend heavily on interdisciplinary cooperation and knowledge exchange. The chapter can promote innovation, close knowledge gaps, and generate context-specific solutions by bringing together scholars, practitioners, policymakers, farmers, and local communities. Reclamation methods can improve damaged soils, guarantee food security, and support sustainable agricultural growth in Africa with focused efforts.

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Rainwater Harvesting Technologies and Soil Moisture Conservation in Marginalised Semi-Arid Soils of Southern Africa



Justin Chipomho, Chimweta Moreblessing, Fortunate Makore,
and Parwada Cosmas

1 Introduction

Approximately 41% of SSA is covered by arid and semi-arid zones (SARZ) (Vohland and Barry 2009). The zones are characterised by short rainy seasons, frequent and prolonged dry spells, low (300–600 mm per annum) erratic rainfall pattern and natural disasters such as cyclones (Kathuli and Itabari 2015; Vohland and Barry 2009). The marginal soils, which are predominant in this region are generally of low inherent fertility and poor nutrient status (Sánchez et al. 2011). The aforementioned abiotic factors combined with biotic stresses (diseases, insect pests, nematodes and weeds) threaten crop production and food security in the region (Gwatidzo et al. 2020; Nyaligwa et al. 2017).

In southern African countries, smallholder farmers contribute significantly to the national grain food reserves and in Zimbabwe close to 60% of national maize supply is from the smallholder sector (Suleiman and Rosentrater 2015). However, maize yield from this sector has remained low with a national average of 1.5 t ha⁻¹ compared to 8 t ha⁻¹ from the commercial sector (Mashingaidze et al. 2009). Declining fertility of marginal soils, environmental and biotic stresses are among the major production challenges faced by smallholder farmers (Tibugari et al. 2019). Moreover, rain-fed crop production remains the popular production system by smallholders' farmers in the arid and semi-arid regions SSA (Lee and Thierfelder 2017). The system is highly vulnerable to the effects of climate change (Naba et al. 2020). Furthermore, in most African countries, irrigation systems are poorly

J. Chipomho (✉) · C. Moreblessing · F. Makore

Department of Crop Science, Faculty of Plant and Animal Sciences and Technology
Marondera University of Agricultural Sciences and Technology, Marondera, Zimbabwe

P. Cosmas

Tugwi-Mukosi Multidisciplinary Research Institute (TMMRI), Midlands State University
(MSU), Zvishavane, Zimbabwe

developed compared to developed nations. African countries irrigate less than 2% of their total cropping area compared to the world average of 18%. African farmers are at high risk of crop failure due to limited irrigation infrastructure (Mabhaudhi et al. 2018).

To avert the effects of climate change, improve crop yield and increase smallholder food security, sustainable solutions, which increase efficient use of water in rain-fed agricultural systems are necessary. This will curb the effects of prolonged dry spells and drought (Meldrum et al. 2018). Installation of the irrigation system is usually the most obvious response to dry-spells and droughts. However, the installation of irrigation technology is costly in setting up requiring high initial capital for running and maintaining the system (Lebel et al. 2015). The high cost of irrigation technology puts it out of reach of poor resourced farmers and only benefits resource endowed farmers. However, the increasing interest in the low cost alternative that is rainwater harvesting techniques provides soil water and or moisture during dry spell periods (Meshesha and Khare 2019). The technologies are simple, cheap and affordable for resource poor smallholder farmers. The RWH techniques reduce surface runoff, increase infiltration and storage of soil water, thus decreasing the effect of moisture stress in dry-land crop production (Ibraimo and Mungambe 2007).

Holst et al. (2007) reported that, water harvesting techniques have long been used to minimize soil erosion as well as increase water storage. Erosion reduces soil fertility when top fertile soil is washed away by surface runoff. Field in situ water harvesting is important since soil erosion in a crop fields may expose plant roots to desiccation resulting in death of plants (Kathuli and Itabari 2015). Furthermore in situ water techniques have been found to improve water infiltration and delay onset of water deficit to a crop thereby reducing crop damage due moisture stress (Matayaya et al. 2017). However, despite the economic viability and the potential that RWH technology has for improving agricultural productivity and livelihoods, its adoption by farmers in SSA is generally low (Singh et al. 2019). The book chapter seeks to review different RWHT, their potential to transform and provide sustainable yields and food security under rain-fed crop production system and generate income for smallholder farmers in marginalised semi-arid soils of Africa's southern region.

1.1 Definition of Terms

- (a) *Marginal soils* is defined as poor physical and chemical soil characteristics and results in low crop productivity with no potential for profit (Bationo et al. 2012). Marginal soils can be categorised by their poor physical characteristics such as rocky, sandy texture, eroded, waterlogged, shallow rooting depth and chemical composition such as low soil fertility, saline, sodic, acidic and chemically contaminated (Bationo et al. 2012).
- (b) *Arid and semi-arid regions* are dry areas that receive little precipitation less than 250 mm per annum while semi-arid regions receive between 250 and

- 500 mm per annum. The regions experience frequent dry spells, drought, high crop failure and livestock deaths due to water scarcity (Vohland and Barry 2009). Families are generally food insecure (Meshesha and Khare 2019). Approximately 45% of Africa fall under dry-lands and Africa is one of the driest continents (Mupambwa 2022). Table 1 shows percentage of area under arid and semi-arid by subregion in Africa.
- (c) *Climate change* according to the United Nations Framework Convention on Climate Change, climate change is defined as significant changes in global weather pattern (wind pattern, precipitation, temperature, and other measures of climate) that occur over a long time (several decades). Evidence available suggests that extreme changes in climate are linked to rising levels of carbon dioxide and greenhouse gasses are directly or indirectly attributed to human activities and this alters the composition of the global atmosphere (Leggett 2020).
 - (d) *Dry-land or rain-fed* is a crop production system, which relies on precipitation received in the area. Close to 65% of sub-Saharan Africa’s population are domicile in rural areas and their agricultural activities are mostly dependent on rain-fed system. Generally the areas experience low and irregular precipitation, and covers 41% of the Earth’s terrestrial surface while 10–20% of the land type is overused and degraded (Vohland and Barry 2009).
 - (e) *Rainwater harvesting* is a technique of collecting runoff water artificially from roof-tops, ground surfaces and intermittent (transient) water sources for productive use. Rainwater harvesting can be distinguished from floodwater harvesting, which is a system of collecting discharge water courses (Lebel et al. 2015).
 - (f) *Micro-catchment water harvesting techniques* is referred to as “within-field catchment system” or overland water flow which is harvested from a short (1–30 m) catchment length. The runoff water is stored in soil profile for plant growth during prolonged periods of moisture stress. Typical examples of micro-catchments include contour bunds and basins or negarim micro-catchments, contour ridges and semi-circular bunds (Kugedera et al. 2018).

Table 1 Percentage of area under arid and semi-arid by subregion in Africa

Sub region	Arid	Semi-arid
Northern Africa (%)	11	7
Western Africa (%)	20	18
Central Africa (%)	0	2
Eastern Africa (%)	27	28
Southern Africa (%)	13	42
Africa total (%)	16	21

Source: Modified from Mupambwa (2022)

2 Internal and External Rainwater Harvesting Techniques

Rainwater harvesting techniques are methods that collect, store and conserve surface water from runoff and use it for domestic and agricultural purposes in arid and semi-arid regions (Lebel et al. 2015). Rainwater can be harvested by capturing run-off from local catchments, roof tops, flood waters from local streams and watershed water conservation. The techniques are designed to increase ground water recharge, provide irrigation water and fresh clean water for domestic use (Mutiso et al. 2018). RWH techniques can help mitigate the effects of dry spells and drought, reduce flooding of low-lying areas and or reduce demand on ground water levels. Besides, rainwater is the first form of water in the hydrological cycle and is the primary source of water for human life. Rainwater harvesting techniques can broadly be categorised as in situ and ex situ (Kugedera et al. 2018).

2.1 *Ex Situ Rainwater Harvesting*

Runoff water is diverted and stored in natural or artificial reservoir for later use. Runoff water is temporarily stored in dugout ponds, diversion bunds, tanks, khadins and haveli water harvesting system (Mutiso et al. 2018).

2.2 *In Situ Rainwater Harvesting*

Rainfall precipitation is collected and conserved as it falls through construction of engineering and or agronomic measures. Some commonly used in situ water harvesting techniques include targa, planting pit, terracing, contour farming, bunding, broad bed furrow system, micro-basins, pot holing, mulching, deep ploughing, ridges and tied ridges (Mudatenguha et al. 2014).

2.3 *Ridges and Tied-Ridge*

The ridges or furrows are blocked with earth ties at intervals known as ‘tied ridges or furrow disking’. Ridges are formed by scooping soil towards the crop plants in the row, forming a 20–60 cm ridge and deep furrow between the rows (Fig. 1, Windmill). Tied or cross-ties are made to increase surface storage and allow more time for rainwater to infiltrate. Cross-ties of soil which hold water within the furrow or between the ridges is constructed at fixed distances to form a series of micro-catchment basins in the field. The height of cross-ties are lower than the ridge so that when the basin is filled the overflow is along the ridge-furrow on the slope. The

Fig. 1 Ridges (Adapted from ZAKIS 2022)



Fig. 2 Tied ridge
(Adapted from ZAKIS 2022)



technology is recommended on field or land with gentle slope less than 2%. Chegutu farmers on sand clay loam soils and drier region of the Zimbabwe recorded yield of above 3.5 t ha⁻¹ from tied-ridge plots compared to 2.1 ha⁻¹ on flat (Fig. 2).

2.4 Planting Pits

This cultivation system consists of circular pits dug and constructed to break the crusted soil surface and to store water and build soil fertility (Kimaru 2017). Pit dimensions vary with type of soil. Crop residue and or livestock manure are incorporated in the soil before sowing in the pits to maintain or improve soil fertility levels. Other forms or designs of pits include Half-moon, Tassa, Chololo, Katumani and Zai pits. Zai pits are the most popular technology developed based on home-grown knowledge and mainly used to improve fertility of poor and bare soils (Fig. 3) The technique works by integrating conservation of harvested rainwater moisture and soil fertility improvement in the pit. The water harvesting technology is commonly used in marginal (350–600 mm) annual rainfall areas.

In the drier parts of Tharaka Nithi in Kenya, Zai pits significantly ($P < 0.05$) modified marginal ferrosols soil (which were infertile, deficient in Nitrogen, Phosphorous, and Zinc highly weathered and leached) by increasing soil pH, Nitrogen and aggregate stability resulting in maize yield increase of 4.3 t ha⁻¹. This was 53.7% higher than the conventional system of growing maize on flat (Kimaru 2017).



Fig. 3 Zai pits (Adapted from Santos et al. [2023](#))



Fig. 4 Targa (Adapted from Wolde et al. [2020](#))

2.5 *Targa*

These are rectangular basin constructed from soil or crop residue at the start of the rain season and laid along contour lines spaced 1.5 m apart (Fig. 4) Targa bund ridges are raised to about 0.2 m above the ground and 0.2 m embankment thickness. The main functions of Targa are to enhance rainwater infiltration. A study carried out on sandy loam soils in Abela Sippa Kebela Wolaita zone, Ethiopia, revealed a significant ($P < 0.05$) increase in maize grain yield and yield components, such as, cob length, dry matter, stover biomass, and grain yield on Targa treatments compared to other water harvesting technologies (Naba et al. [2020](#); Wolde et al. [2020](#)).

2.6 *Fanya Juu Terraces*

Terraces are constructed on land with a slope between 5 and 20% and characterised with light to medium sandy to sandy loam soil types. Bunds on the terrace and ditches may be included after terracing. Terraces are constructed by heaping soil embankment on the up-slope side and make a runoff barrier. The constructed trench from where soil is moved is used for collecting runoff water. On the trench or canal which may vary in dimensions may have 0.6 m deep by 0.6 m wide and 0.7 m soil embankment from the surface (Fig. 5). Rainwater from external local catchments can be directed into the trenches or canals where it's allowed to infiltrate. Plantation crops such as paw-paw, citrus and bananas can be grown constructed in the ditches along the canals. The technology is ideal on land with not more than 5% slope (Fig. 5). Success stories was recorded on hard setting soil in the semi-arid region of eastern Kenya. Fanya juu terraces significantly ($P < 0.05$) improved maize (*Zea mays*) and sugar bean (*Phaseolus vulgaris*) grain yield by 49.8 and 41.6 respectively compared to the control (Njiru et al. 2022). The study recommended the construction of Fanya juu terraces with a ditch of 30 cm for improved maize and sugar bean production in soils in marginal areas (Njiru et al. 2022).

2.7 *Semi-Circular (Hoops) and or Contour Bunds*

These are small embankments made of stones, trash or earth which are constructed along a contour line. Rainwater is trapped by the embankment, and excess water flows down the gradient and bunds will retain moisture. The contour bunds spacing depends on soil type and slope of the land. Steep land slopes require closer contour



Fig. 5 Fanya juu terraces (Adapted from Hanspeter Liniger, undated)

Fig. 6 Contour bunds
(Adapted from Hawkins
and Stanway 2013)



Fig. 7 Semi-circular
bunds (Adapted from
Pradhan and Sahoo 2019)



bunds while gentle slopes have wider contour bunds (Fig. 6). Semi-circular bunds hoops are constructed of earth embankments with tips on the contour. Rainwater is collected within the semi-circular bunds from the area directly above and kept to the depth defined by the bund height and tip positions. Excess water collected in the bunds is discharged from the tips (Fig. 7).

3 Soil Landscape Factors Modified by Rainwater Harvesting Technique

Construction of rainwater RWHT modify landscape functions at different spatial scales. Well documented investigations has recorded that RWHT has impacts on landscape functions such as ground water recharge (Vohland and Barry 2009), wet-land and ecosystem maintenance (Miyasaka et al. 2011), biomass production (Naba et al. 2020), nutrient and floral recycling (Bationo et al. 2012), animal diversity (FAO 2017) water availability and societal incomes (Naba et al. 2020).

3.1 Hydrological Functions

3.1.1 Infiltration

Rainwater harvesting technologies alter water flows in the landscape by improving water permeation at plot scale (Mudatenguha et al. 2014). Reduction in runoff water and water collected by RWH structures significantly increased soil moisture (Kathuli and Itabari 2015). Moreover, the increase in the macro-pores in the soil increases infiltration and soil biological activities this subsequently improves the physico-chemical properties of the soil (Dessalegn et al. 2014). However, enhanced infiltration may result in water logging under poor drainage conditions.

3.1.2 Groundwater Recharge

Interruption by mankind is believed to negatively affect that is deplete the ground water levels (Suhag 2016). According to a report by United Nation Environmental Programme (UNEP), it is estimated that more than 200 million people would live under conditions of water stress by 2050 (UNEP 2014). The use of both in situ and ex situ rainwater harvesting techniques is therefore a means to increase ground water recharge thereby enhancing water availability. Rainwater harvesting technologies increase ground water recharge though increased water infiltration, reduced runoff when water is collected into ponds and reservoirs. Studies by Suhag (2016) concluded that RWHT are an effective tool of replenishing ground water resources.

4 Crop Resilience in Dry-Land System, Biomass, and Yields

Generally, from (Table 2), rainwater harvesting technologies have a pre-eminent role to play in the collection and utilisation of rainwater. This enables field crop to tolerate extended dry or moisture stress periods. Rainwater harvesting technologies have been found to increase crop biomass and grain yield on marginal soils in semi-arid regions (Kugedera et al. 2018), restore degraded soil types and reduced the impact of moisture (Chipomho et al. 2018), increase in *Zea mays* yields on marginal soils in semi-arid regions of Africa by 14–50% though bridging water deficits (Lebel et al. 2015). However, studies on the effects of RWHT on biomass and grain yield have mainly been carried out on cereal crops (Table 2) such as sorghum (Ayala et al. 2019) and maize (Naba et al. 2020) and pearl millets (Mutiso et al. 2018).

Table 2 Examples of research on rainwater harvesting techniques and their impact on crop biomass and yield in Africa

Country	Rainwater harvesting technology evaluated	Summary of findings in marginal soil types	Source
Ethiopia	Targa, Trus, tied ridge, and farmers' practice	Targa resulted in significantly higher grain yield, plant height, cob length. Biomass in the following order Targa (8843 kg/ha), Tie ridge (6250.9 kg/ha), Trus (5784 kg/ha) and Control (4525.6 kg/ha)	Wolde et al. (2020)
Ethiopia	Targa, tie-ridge and zai pits compared to control	On sandy loam soils, higher maize grain yields were recorded from targa (7150 kg ha ⁻¹) and tied ridges (6190 kg ha ⁻¹) compared to control (4900 kg ha ⁻¹) and zai pit (4500 kg ha ⁻¹)	Naba et al. (2020)
Kenya	Basin technique, tied ridge technique and planting on flat as (control)	Tied ridges constructed on very deep dark reddish brown to dark red friable sandy clay to clay soil, increased pearl millet grain yields by up to 262 kg ha ⁻¹ and Stover yield by a maximum of 638 kg ha ⁻¹ over control	Mutiso et al. (2018)
Ethiopia	Open ridges, tied ridges, circular pit, and farmer practice i.e., flat (control)	In situ water harvesting technologies constructed on sandy clay loam soils, increased sorghum grain yields from 20 to 83.3% in the study area	Ayala et al. (2019)
India	Rainwater storage structure (40 M × 40 M × 3.5 M) as an option to increase production on farm	The rainwater storage investment resulted in marked increase in goat production, intercropping, fodder production crops and grasses, and fish farming which increased farm income	Singh et al. (2019)
Zimbabwe	Tied ridges, planting pits and conventional tillage	Construction of planting pits and tied ridges on sandy soils resulted in higher and similar sorghum Stover and grain yields of 9.20 and 3.66 t/ha and was significantly ($P \leq 0.05$) higher than the control (planting on flat) treatment which recorded sorghum Stover and grain yield of 4.58 and 1.80 t/ha respectively	Kugedera et al. (2018)
Africa	Rainwater harvesting (RWH)	Construction of RWHT on marginal sandy soils increased <i>Zea mays</i> yields across Africa by between 14 and 50% by bridging water deficits	Lebel et al. (2015)

(continued)

Table 2 (continued)

Country	Rainwater harvesting technology evaluated	Summary of findings in marginal soil types	Source
Kenya	Tied ridges, zai pits, semi-circular hoops, stone bunds, negarims, contour bunds, terraces, trapezoidal bunds, micro-catchments	On marginal sandy soil, Zai pits, tumbukiza combined with soil fertility practices increase crop yields by 4–10 times in comparison to conventional system. Tied-ridging combined with soil fertility improvement increases crop yields by 100–300% compared to conventional	Kathuli and Itabari (2015)
Rwanda	Pot holing, tied ridging and mulching compared to control	Construction of RWHT on fersiallitic oxisols sandy loam soils, with pH of 5.8 and 3.2% organic matter increased maize grain yield by 49.6, 103 and 136% in pot-holing, tied ridging and mulching treatments, respectively compared to flat planting that recorded (1593 kg ha ⁻¹)	Mudatenguha et al. (2014)
Zimbabwe	The role of socio-economic factors on performance of in situ water harvesting technologies	Results showed a strong correlation between performance and resource status ($P = 0.004$). The author concluded that resource ownership was a key factor in the farmers' ability to scale out rainwater harvesting technologies (RWHT). The performance of RWHT was significantly linked to resource status	Munamati et al. (2009)

5 Biodiversity Under Soil and Moisture Conservation

Rainwater harvesting technologies have been recorded to impact biodiversity, that is, structural heterogeneity, animal, and floral diversity. A positive relation exists between rainwater harvesting technologies, plant biomass, species diversity and abundance. The increase in plant biomass and species abundance subsequently benefit animals in form of food and shelter (Panday et al. 2019). Increase in plant biomass allows more complex trophic chains to occur. Field studies in Africa have shown increase in animal species and individuals' numbers as area under vegetation patches increase (Singh et al. 2019). However, if RWHT structures are not suitably designed, stagnant water may be an ideal site for breeding of disease-causing vectors such as mosquitoes which cause malaria, snails bilharzia and midges blue tongue in sheep (Vohland and Barry 2009). Furthermore, when natural vegetation is replaced with cropping systems, changes in composition of both domestic and wild animal communities may occur. Generally, natural vegetation tends to support more animal species compared to establishment of a monospecific field crop.

Rainwater harvesting practices improve plant biomass production per unit area thereby modifying the spatial structure i.e., heterogeneity/patchiness of the ecosystems. Documented evidence shows that RWH practices can increase vegetation cover in arid landscape (Lee and Thierfelder 2017). The association between rainwater harvesting practices and landscape heterogeneity refers number of plant and composition of patches, spatial and temporal structure of the patches. Water harvesting technologies positively increase biomass of crop plants, fodder grasses and trees species on marginal soil in semi-arid regions. However, this area has not been well investigated.

6 The Role of Water Harvesting Technologies in Sustainable Livelihoods

6.1 Food Security

Sustainable increase in crop yields is vital for rural community food security. Documented evidence has shown that RWHT in many cases resulted in improved crop biomass and grain yield compared to planting on flat (Mudatenguha et al. 2014; Singh et al. 2019; Waswa et al. 2020). Some studies have shown that RWH structures increase crop resilience to moisture stress and minimises crop failure due to dry spell and drought and this enhances food security (Parwada et al. 2022). Other mechanisms include prolonged vegetation period caused by early planting and availability of supplementary irrigation from ponds and pools. Furthermore, RWH technologies reduce soil surface water runoff and enhances water infiltration and favours groundwater recharge and refilling of open ponds and wells for future water use as irrigation water.

6.2 Income/Social Balance

Despite low adoption of RWHT, documented evidence suggests positive effects on farmer's income. The general increase in crop yields on marginal soils in the semi-arid regions means farmers will have surplus farm produce which can be sold to generate income. However, farmers are generally hesitant and reluctant to invest time and money in RWH structures due to lack of security of land tenure and ownership in communal areas.

7 Conclusion

The general conclusions of the review are consistent with research on rainwater harvesting techniques in other arid and semi-arid zones in other parts of the world. Several documented evidence suggest that water harvesting techniques have an overall positive effect on soil fertility of marginal soils, landscape functions, crop biomass and yields. Rainwater harvesting techniques reduce surface runoff, increase infiltration and storage of soil water, thus decreasing the effect of moisture stress in dry-land crop production. The technologies are simple, cheap and affordable for resource poor smallholder farmers. The technologies are appropriate for sustainable crop production and food security for farmers in arid and semi-arid zones through improved crop resilience moisture stress.

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