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Food Security for African Smallholder Farmers

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Chapter 19
Liquid Gold: Harnessing the Potential of Digestate to Enhance Smallholder Farmer Food Security and Livelihood

Ashira Roopnarain, Busiswa Ndaba, Haripriya Rama, Linda Obi, Maryam Bello-Akinosho, and Muyiwa Akindolire

Abstract Smallholder (SH) farming systems drive many economies in Africa and are one of the main sources of food and income to the poorest in both urban and rural areas. Improvements of the farming system is imperative to ensure food security and poverty reduction. A holistic SH farming approach that promotes resource recycling will ensure sustainability and productivity of SH farms. Anaerobic digestion (AD) is important to a holistic SH farming system. Anaerobic digestion aids in waste management and results in the generation of biogas as well as a nutrient-rich digestate. The value of the generated biogas has been widely publicised; however, the importance of the produced digestate is less known. This chapter aims at revealing the myriad of applications of digestate that are relevant to SH farming systems. These applications include its use as an organic fertilizer, in seed priming, as irrigation water, as a biopesticide, in aquaculture and livestock management as well as in several bioprocesses. Simple digestate post-treatment methods will also be highlighted. Overall, this chapter is aimed at improving understanding of the potential of digestate to promote its utilisation, together with the generated biogas, in a holistic farming approach thereby maximising benefits associated with AD.

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19.1 Introduction

The success of any farming system is closely related to the availability of several resources, including nutrients, energy, water, carbon, labour as well as finances, that collectively drive farming activities. Holistic farming systems promote the optimal reuse of such resources to maximise sustainability, efficiency and productivity of the farming process (Orskov et al. 2014). With the current projections of an increase in the population in sub-Saharan Africa (SSA) to approximately 2.5 billion by 2050 (Worldometers.info 2021) and the gradual decline in the productivity of SSA farmlands (Masso et al. 2017), it is imperative that urgent efforts, such as holistic farming, be implemented to ensure food security. Considering that smallholder (SH) farming systems contribute to as much as 80% of the food that is consumed in SSA, it is pertinent that SH farmers receive the necessary skills, technology and guidance to sustain and improve food productivity (Kamara et al. 2019). Holistic farming approaches are of particular importance in resource-poor SH farms where recycling of the limited resources is imperative to meet the ever-escalating food requirements. More so, such farming approaches may aid in transitioning SH farmers from subsistence to commercial level.

The integration of biogas digesters on SH farms may form a central component to the transition to holistic farming. Biogas digesters enable the provision of energy to households, along with the recycling and cleaning of wastewater and the production of a digestate, which could potentially be utilised for several applications, including as an organic fertilizer (Orskov et al. 2014; Roopnarain and Adeleke 2017; Roopnarain et al. 2019; Roopnarain et al. 2020). Smallholder farmers globally have adopted the process of anaerobic digestion (AD) for the treatment of organic waste such as animal manure and plant residues in small-scale biogas digesters constructed on their farms. Anaerobic digestion involves the breakdown of organic matter (feedstock) by anaerobic microorganisms in an oxygen-free digester into biogas and digestate (Groot and Bogdanski 2013). The process occurs in four stages, that is, hydrolysis, acidogenesis, acetogenesis and methanogenesis (Fig. 19.1) (Roopnarain and Adeleke 2017). Much attention has been placed on the product of methanogenesis, methane, due to its elevated energy content (50–55 MJ/kg) (Rajendran et al. 2020). On SH farms, methane produced during the AD process can be combusted for cooking, heating and lighting purposes, amongst others (Fig. 19.2). However, methane is not the only valuable product of the AD process, another oftentimes overlooked product of the process with immense value is the digestate, which is the organic matrix that remains after AD that has substantial agronomic potential (Nkoa 2014).

During the course of the AD process, not all of the components of the feedstock are converted to biogas. Easily transformable carbon compounds are converted to

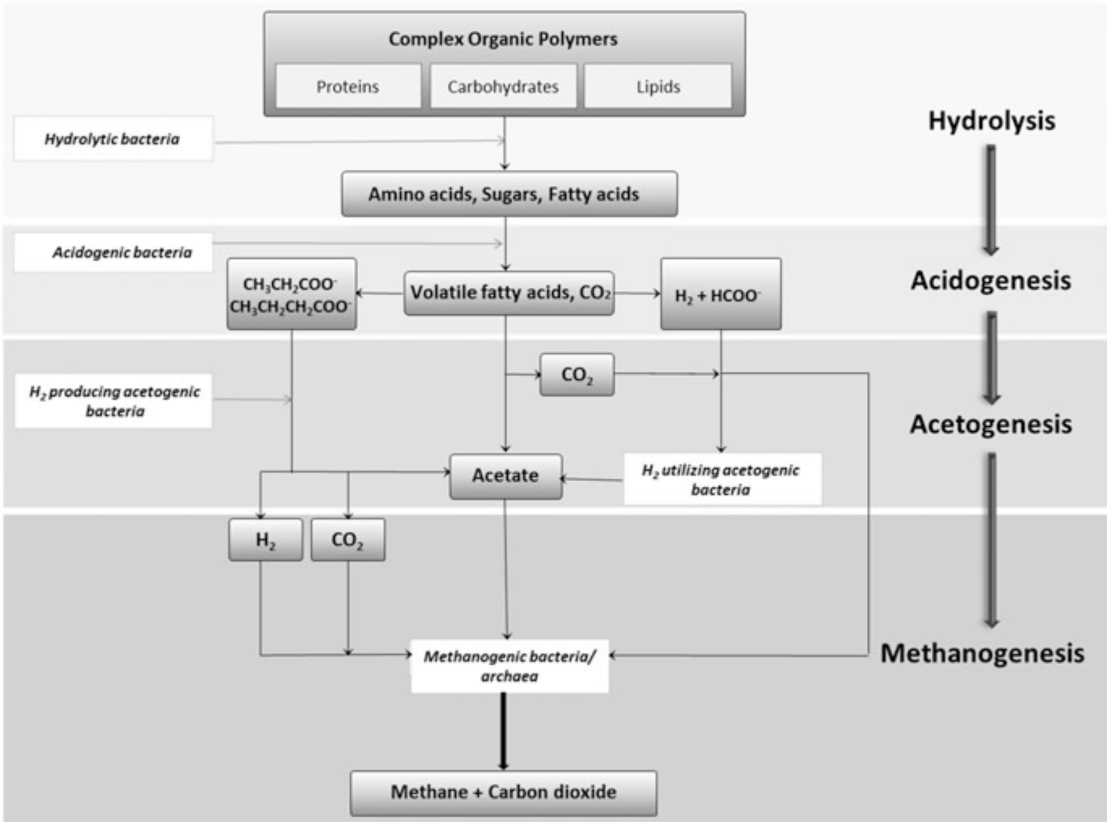

Fig. 19.1 Main stages of anaerobic digestion of organic matter (Adapted with modifications from Roopnarain and Adeleke (2017))

methane and carbon dioxide, whereas more recalcitrant carbon compounds remain in the digestate. Moreover, nitrogenous compounds are converted to ammonium-nitrogen, which remains in large quantities in the digestate along with other macro and micronutrients (Głowacka et al. 2020). When comparing the products of AD with regard to volume, the volume of digestate produced surpasses that of biogas. Approximately 50–85% of the feedstock input into an AD system is released from the system in the form of digestate (Primmer 2021). The large amounts of digestate produced during the AD process justifies its valorisation to ensure that a circular economy and sustainable development is achieved (Czekała et al. 2020). Moreover, valorisation of all AD products may aid in accelerating the payback period for the AD system thereby promoting technology adoption by SH farmers and urban households alike.

The composition and quantity of digestate is a function of the feedstock that is introduced into the digester as well as the digester configuration and fermentation process implemented during AD (Nkoa 2014; Czekała et al. 2020). The properties of the digestate in turn dictate potential applications. For example, liquid digestate that is produced upon digestion of poultry litter, which is rich in N, is more suited for the cultivation of vegetables, cereal crops and grasses. Whereas, liquid digestate derived from AD of cattle manure is more applicable for the cultivation of leguminous plants or crops that are in the blooming or reproductive phase, as it is rich in K and P

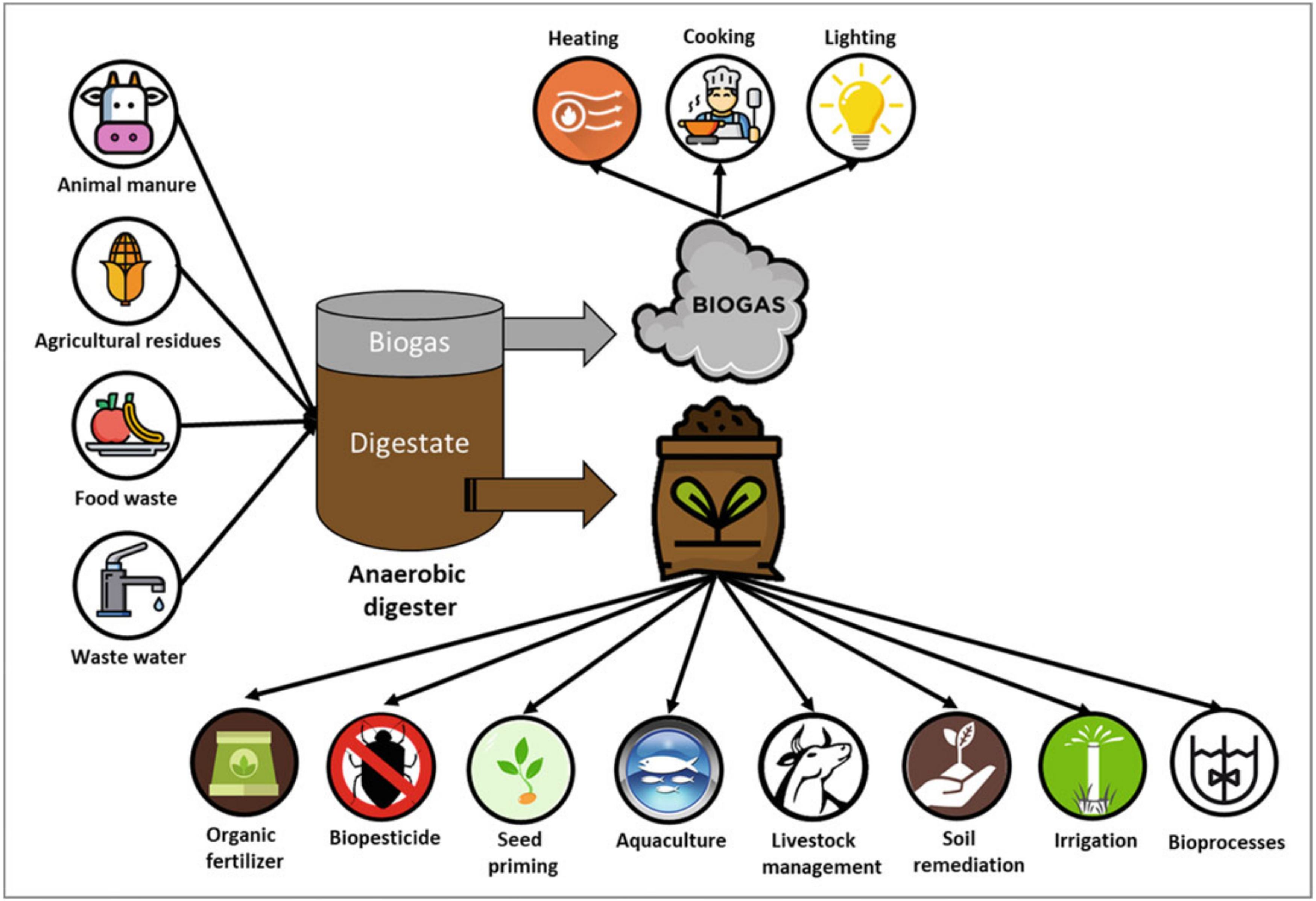

Fig. 19.2 Overview of potential applications of biogas and digestate in smallholder farming systems (Adapted from Nkoa 2014 and Baştabak and Koçar 2020)

(Clemens and Morton 1999; Nkoa et al. 2001; Nkoa 2014). Overall, the properties most times indicate that digestate can be successfully utilized as a fertilizing agent (Tambone et al. 2017). However, due to its nutrient-rich nature, several additional applications of digestate exist (Fig. 19.2).

With the increase in the number of household biogas digesters being constructed across Africa as a result of several national domestic biogas programmes (Orskov et al. 2014), it is imperative that the full potential of such systems be harnessed to ensure that system abandonment is minimised and the overall outlook of the technology is not tainted. Harnessing the full potential of AD technology requires the valorisation of all products, that is, biogas as well as the digestate. The value of the generated biogas has been widely publicised; however, the importance of the produced digestate is less known. Hence, this chapter seeks to highlight the properties of digestate as well as the multitude of applications and benefits associated with digestate use. Moreover, low-cost digestate treatment methods that are applicable to SH farming systems will be elaborated on and recommendations on how to maximise digestate use will be provided. Ultimately, this chapter is aimed at improving understanding on the potential of this valuable resource by integrating its use in holistic SH farming systems, thereby equipping SH farmers that possess anaerobic digesters with the necessary tools to improve their food security and potentially transition from subsistence to commercial level.

19.2 Physico-Chemical and Biological Properties of Digestate

Digestate, the solid-liquid residue of AD, consists mainly of macronutrients (N, P and K), micronutrients (B, Fe and Mn), as well as undigested organic matter (OM) (Plana and Noche 2016; Tampio et al. 2016; Mukuna et al. 2021). Consequently, digestate is commonly land applied as a nutrient-rich organic fertilizer when both the quality and characteristics are adequate for field application (Tambone et al. 2010). The composition, physico-chemical and biological properties of digestate presented in Table 19.1, are major indicators of its quality and key determinants of its possible end use (Teglia et al. 2011; Nkoa 2014; Tampio et al. 2016). These properties are dependent on several parameters including type and composition of feedstock (Tambone et al. 2010), AD process parameters (temperature, inoculum used and hydraulic retention time (HRT)) as well as digestion type (dry, wet, single- or multi-stage). For instance, the digestate recovered from wet AD contains low dry matter (DM) content; hence its characteristic liquid consistency in comparison to that which has undergone dry digestion (Logan and Visvanathan 2019), since dry AD promotes the production of digestate with elevated DM content (Momayez et al. 2019). No less important is the influence of feedstock on digestate characteristics (Sogn et al. 2018). With a wide range of feedstock or mixtures of feedstock being employed as substrates for AD, a high level of inconsistency is expected in the

Table 19.1 Physico-chemical properties of digestate derived from anaerobic digestion of various feedstock

Feedstock	DM (%)	OM	pH	C/N	TN	P	K	NH_4-N	Reference
Cattle manure and clover/grass	10.7	–	8.21	8.5	47, 31.4 mg/g DM	–	–	15.5 mg/g DM	Barduca et al. 2021
Cattle slurry, maize silage and haylage	5.83	–	8.53	–	31.4 g kg^{-1} DM	11.7 g/kg DM	55.9 g/kg DM	–	Barłóg et al. 2020
Food waste	1.9–7.8	12.3–63.7 g kg^{-1} FM	7.6–8.3	1.5–3.3	4.7–8.7 g/kg FM	0.11–0.33 g/kg FM	1.9–3.2 g/kg FM	1.7–4.5 g/kg FM	Tampio et al. 2016
Agricultural residues (corn silage and grass silage)	6.6–9.3	4.8–6.9%	7.6–8.0	–	3.6–4.9 kg/t	–	–	1.3–2.4 kg/t	Drosg et al. 2015
Crop residues	6.2–8.6	4.8–6.2%	7.4–7.9	–	3.9–5.2 kg/t	–	–	1.5–2.5 kg/t	Drosg et al. 2015
Agricultural waste	4.3–6.6	–	7.8–8.5	11.3–17.19	2.0–3.1 g/kg	460–1090 mg/kg	1155–1225 mg/kg	–	Głowacka et al. 2020

DM dry matter, *OM* organic matter, *C/N* carbon to nitrogen ratio, *TN* total nitrogen, *FM* fresh matter produced digestate imparting varying qualities, which ultimately dictates its application. Thus, a sound knowledge of the defining characteristics of every digestate is required to establish digestate quality and assess its potential use. Quality assessment will in turn aid in maximizing agricultural and environmental benefits and minimizing limitations, as depicted in Table 19.2, and eventually alleviate environmental impacts of unfit products (Beggio et al. 2019).

19.2.1 Dry Matter Content of Digestate

Due to the degradation of OM during the AD process, digestate has lower DM content compared to the feedstock (Drosg et al. 2015). The DM content of digestate varies widely from 1.9 to 10.7% (Table 19.1) (Insam et al. 2015; Tampio et al. 2016; Barduca et al. 2021). Variations in DM concentration of digestate can be attributed to factors related to the reactor configuration (wet or dry digestion), process parameters (HRT and loading rate) and feedstock type (Teglia et al. 2011; Tampio et al. 2016). For instance, DM of wet AD and dry AD digestate differs greatly from each other as DM of the former can be as low as 1.5%, whereas DM content of above 15% has been reported for digestate obtained from high solid content feedstock (Drosg et al. 2015). Since SH farmers have surplus diverse agricultural wastes, including crop residues that are high in lignocellulosic biomass, they have a propensity to generate high DM digestate. This would be advantageous to farmers for such digestate could be managed easily without the need to undergo solid-liquid separation, reducing associated costs on financially constrained SH farmers.

Based on the moisture content (MC), digestate can be categorised into three groups: whole, liquid or solid digestate (Plana and Noche 2016). Whole digestate is the digested material obtained at the end of AD in the form of solid-liquid suspension and is characterised by a high MC with less than 15% DM. Due to its high volume, transportation costs become a major obstacle for the application of whole digestate for agricultural purposes, especially when farms are situated far from AD plants (Plana and Noche 2016). In an effort to reduce water content and concentrate the nutrients of digestate to ease production economy, whole digestate is subjected to solid-liquid phase separation (Fuchs and Drosg 2013; Plana and Noche 2016). After separation, the liquid fraction contains most of the soluble N and K while the solid fraction retains most of the digestate P and less than 20% DM (Logan and Visvanathan 2019; Sigurnjak et al. 2017).

On the other hand, low DM content can be beneficial, making digestate easier to pump and apply as an organic fertilizer or irrigation water, with a reduced need for stirring, compared to raw animal manure (Seadi et al. 2008). This is of particular importance to SH farmers where digesters are situated on farms and the resulting digestate is intended for on-farm use, alleviating the costs associated with transportation of large volumes of liquid digestate. Moreover, crop burns are avoided during such application since digestate flows more easily off the plants' vegetable parts

Table 19.2 Overview of limitations and strengths of digestate application based on its physico-chemical and biological properties

Parameters/ properties of digestate	Advantages/strengths	Disadvantages/limitations
Soil nutrients	*Fertilizer value* • Improves fertilizer quality of animal manure • Provides important plant nutrients resulting in improved crop yield. Increased N-availability for crop growth • Mitigates negative impacts of mineral fertilizer and enhances environmental sustainability • Farmers can also benefit from the sale of excess digestate as an organic fertilizer *Soil amendment properties* • Improves soil quality by increasing bulk density, humus balance and overall soil structure	*Leaching potential* • Given digestate's high nutrient content, contamination of surface and groundwater through leaching is a serious concern (Sigurnjak et al. 2017) • High NH_4^+-N may lead to NH_3 volatilization and phytotoxicity in plants
Heavy metals	*Minimal heavy metals in digestate from smallholder waste streams* • Residues from household and agricultural wastes are of little concern regarding heavy metal contamination (Zirkler et al. 2014)	*Possible persistence of heavy metals* • Increased risks of soil contamination with toxic materials including heavy metals as well as organic pollutants, especially in digestate obtained from sewage sludge and biowaste (Tampio et al. 2016)
pH	*Soil acidity control due to alkaline pH of digestate* • Contributes to soil acidity control and can reduce overall running costs through replacement of expensive liming materials (Różyło et al. 2015; Ogwang et al. 2021)	*N losses associated with elevated digestate pH* • Elevated NH_3 volatilization during digestate spreading due to alkaline pH of the digestate, particularly for digestates with pH $>$ 8 (Nicholson et al. 2017)
Biological property	*Pathogen removal under thermophilic conditions* • Under thermophilic conditions, the AD process contributes to efficient pathogen removal reducing the risk of human infections and environmental contamination (Nakamya et al. 2020) *Positive effects on soil microbes* • Stimulates soil microbial activity associated with plant growth (Głowacka et al. 2020) *Reduction in antibiotic resistance genes (ARGs)* • Contains a lower level of ARGs in comparison to undigested raw manure (Sun et al. 2020; Lukehurst et al. 2010).	*Incomplete pathogen removal under mesophilic and psychrophilic conditions* • The use of mesophilic or psychrophilic conditions during AD does not guarantee pathogen-free digestate

(continued)

Table 19.2 (continued)

Parameters/ properties of digestate	Advantages/strengths	Disadvantages/limitations
	Odour and crop burn reduction • Reduction of odour emissions and prevention of crop burns (Insam et al. 2015; Seadi et al. 2008)	*Odours emitted if system is not well maintained* • Neglected anaerobic digesters may result in the emission of odours.
	Weed seed destruction under thermophilic conditions • The AD process eliminates weed seeds resulting in digestate with minimal risk of weed spread (Lukehurst et al. 2010)	*Elevated HRT for weed seed destruction under mesophilic and psychrophilic conditions* • Elevated HRT may be required for the destruction of weed seeds under mesophilic and psychrophilic AD conditions (Lukehurst et al. 2010) • Seeds with a tough cuticle may not be inactivated during AD

compared to raw manure, which reduces the time of direct contact between digestate and the aerial parts of the plant, reducing the risk of leaf damage (Seadi et al. 2008).

19.2.2 Total Organic Matter in Digestate

Organic matter decreases during the AD process due to microbial hydrolysis of easily degradable (labile) matter in the feedstock; however, OM content in digestate is primarily related to feedstock composition (Tambone et al. 2009). Digestates from feedstock with a high degradability are characterized by low OM while agricultural biomass, that are rich in fibrous materials, lead to a high OM digestate (Teglia et al. 2011). As a result, OM content of digestate resulting from the decomposition of highly degradable feedstock such as food waste can drop to as little as 6% (Tampio et al. 2016) whereas digestate from agricultural residues and cattle slurry, such as the digestate mostly evident on SH farms, are richer with greater than 60% OM content, and can, therefore, be utilized to improve soil OM (Nõlvak et al. 2016). However, the ability of digestate to contribute to soil OM is not only dependent on the level of OM contained, but also influenced by the composition of its recalcitrant fractions (Möller 2015). Anaerobic digestion process modifies digestate OM via conversion of readily available OM into biogas and preservation of recalcitrant components such as lignin and complex lipids, thus contributing to the production of digestate rich in recalcitrant OM (Tambone et al. 2009). A biomass characterized by high-recalcitrant OM is considered to be biologically stable and could be utilized to maintain soil humus balance making it a suitable organic amendment material (Mukhuba et al. 2018). In recent years, intensive agriculture has promoted soil degradation, loss of soil fertility and OM, hence recycling of digestate rich in recalcitrant OM has an important role of resource conservation and soil quality maintenance in agricultural systems, particularly in SSA (Mukhuba et al. 2018; Peng and Pivato 2019; Głowacka et al. 2020; Ogwang et al. 2021).

19.2.3 Carbon-to-Nitrogen Ratio of Digestate

In comparison to raw manure, digestate typically has a lower carbon to nitrogen (C/N) ratio due to degradation of total organic carbon (TOC) and elevated N concentration (Tambone et al. 2009). A decrease in C/N ratio from 13.43 to 3.43 has been reported during AD process of mixtures of energy crops, cow slurry, agro-industrial waste and municipal solid waste (Tambone et al. 2009). As major components of OM, the concentration and proportion of C-to-N is essential as an unbalanced ratio can have negative effects on soil microbes by influencing N turnover in agriculture (Johansen et al. 2013). The C/N ratio is often used to describe the balance between these elements and is an important indicator of digestate stability, nitrogen availability, nutrient balance and agronomic value (Nkoa 2014). Organic matrix with high C/N ratios (greater than 30) utilizes soil nitrogen to aid decomposition, limiting its crop availability (Alburquerque et al. 2012a, b), and therefore contributes to N-immobilization if applied to soil. On the contrary, those with low C/N ratios (less than 20) present higher amounts of total N with possible elevated levels of mineralized, plant-available N (Głowacka et al. 2020). Generally, for agricultural residue digestate, a low C/N ratio of 11.3 to 17.1 has been described, suggesting their N-availability as well as their N-fertilization property (Głowacka et al. 2020). Application of low C/N digestate by SH farmers has the potential of enhancing soil N content and crop yield.

19.2.4 Total Nitrogen in Digestate

During the AD process, organic nitrogenous compounds such as proteins are broken down into mineralised ammonium-nitrogen (NH_4-N), which is easily available to plants (Alburquerque et al. 2012a, b; Mukhuba et al. 2018). In comparison to mineral fertilizers, cow dung and pig slurry, digestate has been shown to contain a higher amount of mineralized N and, therefore, produces better crop yield (Risberg et al. 2017; Mukhuba et al. 2018). High N content in digestate is advantageous for agriculture considering that N is an essential plant nutrient, and due to its increased bioavailability post-AD, digestate integration in the fertilization programme by SH farmers is promoted.

Considering that digestate has higher amount of mineralized nutrients, particularly NH_4-N, than raw manure, potential contamination of surface and groundwater through leaching following land application is a serious concern (Sigurnjak et al. 2017). However, nutrient leaching potential of digestate is influenced by many variables such as soil texture, topography, time of application, fertilization strategies and precipitation. Thus, the utilization of good agricultural practices, general measures for quality control as well as safe handling, storage and application can limit the risk associated with digestate valorisation (Alburquerque et al. 2012a, b; Logan and Visvanathan 2019). Moreover, it has been shown that digestate has low leaching potential relative to inorganic fertilizers, making them a better alternative (Tshikalange et al. 2020).

19.2.5 pH of Digestate

Most digestates are usually alkaline having pH values in the range of 7.6 to 8.5 as a result of volatile fatty acid (VFA) degradation and NH_3 production during the AD process (Table 19.1) (Teglia et al. 2011). The pH value influences the effect of digestate on soil quality and plant growth. Low pH is a major constraint for crop production in SSA and is considered the most important plant growth-limiting factor in certain parts of South Africa where 85% of arable land is affected by acidic soil (Helberg 2019). Low pH affects the activity of beneficial soil microbes with a resulting negative effect on the degradation of OM, nutrient mineralization and immobilization, uptake and utilization of nutrients by plants and subsequently on crop growth and yield. Biogas digestate offers a sustainable and cost-effective solution that could be adopted to overcome the constraints arising from soil acidity and offset expensive liming materials for acidic soil (Różyło et al. 2015; Mukhuba et al. 2018; Głowacka et al. 2020; Mukuna et al. 2021; Ogwang et al. 2021).

19.2.6 Phosphorus and Potassium in Digestate

During AD, the concentrations of P and K are not significantly affected, and their level in digestate is majorly influenced by the concentration of these elements in the feedstock (Drosg et al. 2015; Insam et al. 2015). Generally, digestate contains 1% P and 1.4% K (Tampio et al. 2016). Digestate showed similar fertilizing potential to high-soluble mineral P fertilizer such as Triple Super P (TSP) and undigested slurry due to its high content of plant-available P and K as well as other macronutrients, and therefore represents a valuable source of these essential elements (Bachmann et al. 2016).

19.2.7 Biological Properties of Digestate

Interest in the biological composition of digestate has been heightened by concerns that many pathogenic microbes may enter the environment through digestate when applied on agricultural land. While digestate is not free of microbes, studies have indicated the efficacy of AD process in reducing potentially pathogenic bacteria (Avery et al. 2014; Nakamya et al. 2020) as well as deactivating pathogenic fungi (Bandte et al. 2013). In addition to enteric pathogen reduction, the presence of plant growth-promoting bacteria (PGPB) in digestate, which contributes to improved plant nutrient uptake, accentuates its fertilizer potential (Mukhuba et al. 2018). Furthermore, the effects of digestate on microbial activities were shown to be similar to those of cattle slurry, as the addition of digestate to the soil did not negatively affect soil microbes, suggesting their usage as fertilizer will not upset microbial activity in the soil (Risberg et al. 2017). Rather, numerous studies have described the enhancement of soil microbial diversity and activity related to plant growth through improved soil enzymatic activity in response to application of digestate in comparison to other mineral fertilizers (Głowacka et al. 2020; Möller 2015). Moreover, the AD process has been shown to contribute significantly to a reduced level of antibiotic resistance genes (ARGs) in comparison to raw manure; thus, application of digestate as fertilizer probably poses a limited risk of spreading ARGs in the environment (Sun et al. 2020). In summary, the AD process does not only increase the agronomic value of feedstock through their transformation into nutrient-rich digestate but also improves other important properties of digestate suggesting them as good candidates for an array of applications by SH farmers.

19.3 Applications of Digestate

Digestate is used in several applications such as soil amendment and fertilization, disease and pest control, seed pre-treatment, aquaculture, microalgal cultivation, hydroponics, energy production, nutrient recovery, livestock management, bioadsorbent production, building material production, irrigation, soil remediation and as substrates in bioprocesses (Zhao et al. 2014; Nagarajan et al. 2019). In fact, a paradigm shift in the focus of AD has been suggested from biogas optimization to 'integrated biogas–digestate optimization'. The need to valorise digestate is now more attractive than ever; it is deemed necessary in order to enhance food security and overall to achieve a circular economy and holistic farming, which is particularly important in resource-poor SH farming systems (Logan and Visvanathan 2019).

In developing African countries, SH farmers represent a vast population of rural dwellers whose rate of adoption of biogas technology is relatively slow, in comparison to other countries such as India and China, as they are restricted by political, financial and sociocultural factors (Roopnarain and Adeleke 2017). This also applies to the utilization of digestate for the purpose of sustenance of agriculture in developing African countries. Sub-Saharan Africa is plagued with the crisis of food insecurity, which is often a result of limited soil N content for the production of crops in several regions (Ndambi et al. 2019). In the few SSA regions where utilization of digestate for agronomic purposes has been adopted, it has contributed to enhanced soil fertility as well as improved crop production for SH farmers. Batchelor et al. (2017) reported on the improved income generation and increased production rate of staple foods such as potato, maize and tomato in some African countries resulting from the application of digestate as a substitute to synthetic fertilizers. Many European countries have set regulations on the handling, pre-treatment, processing, transportation and storage of digestates (Aso 2020). There are no set regulations for digestate handling, storage and application in most SSA countries yet; however, South Africa has a set regulation for the utilization of digestate as a soil ameliorant (DAFF 2018). In place of regulations for digestate management, some SSA countries have policies and regulations for manure handling and application by SH farmers (Ndambi et al. 2019). Nevertheless, some studies have pointed out the indiscriminate disposal of livestock manure in Africa as opposed to productive applications; this poses a threat to public health and the environment at large (Lederer et al. 2015). Productive applications of livestock manure include AD to generate digestate and biogas for different uses. Selected digestate applications relevant to SH farming systems are elaborated on below.

19.3.1 Digestate as Soil Amendment or Organic Fertilizer

Digestate is rich in both macro and micronutrients as well as OM. Nutrients in feedstock are conserved during AD and converted to a more mineralized form, which are better accessible to plants (Logan and Visvanathan 2019). Digestate has, therefore, been applied globally in a variety of soils and crops to amend soil and enhance soil nutrients (Islam et al. 2010; Yu et al. 2010; Alburquerque et al. 2012a, b; Al Seadi et al. 2013). Application of digestate on farmland is typically done by surface spreading, injection, trailing hose or by incorporation through trailing shoe (Nkoa 2014). Since many SH farmers have anaerobic digesters on their farms, digestate, therefore, becomes an inexpensive source of soil nutrients, reducing the use of synthetic chemical fertilizers while minimizing the huge cost thereof and associated carbon footprint as well as energy requirement for manufacture of synthetic fertilizers (Alburquerque et al. 2012a, b; Barzee et al. 2019; Barłóg et al. 2020). It also prevents downstream effects of such chemical fertilizers, which include deterioration of soil structure and eutrophication due to runoff of chemicals into water bodies (Baştabak and Koçar 2020). Digestate application on farmlands recycles nutrients, improves soil OM (Pezzolla et al. 2012) and increases both macro and micronutrients in soils and plants (Głowacka et al. 2020; Mukhuba et al. 2020). When digestate is used to amend soil for vegetable crops, it is found suitable even at low soil temperatures, which is often the case for crops that have to be planted in cold seasons as early cultivations and that have high N requirements (Möller and Müller 2012). Incorporating fertilization with digestate by SH farmers would go a long way in enhancing their food security, enabling them to maintain a circular economy and holistic farming on their farms and empowering them to contribute to ensuring national food security.

Reclamation or harvesting of nutrients and compounds from digestate is another possible option as some feedstock used for the metabolic process of AD are rich in macronutrients and compounds which usually persist in the digestates (Aso 2020). Reclamation of nutrients from digestate through ammonia stripping (ammonia recovery) and formation of struvite (precipitation and crystallization of phosphorus) is of agronomic benefit as these reclaimed nutrients are essential plant nutrients and potential fertilizers (Vaneeckhaute et al. 2017). However, the cost implication of the process of reclamation of nutrients from digestate poses a challenge to SH farmers (Shi et al. 2018). Nevertheless, SH farmers could improvise by concentrating the digestate using affordable technologies like filtration, sedimentation and decantation. The liquid portion of the digestate could be sprayed or injected into the soil for enhanced fertilization. Surplus biomethane from the biogas plant could also be combusted and the generated heat used for evaporation of the liquid portions of digestate in cases where the solid fraction is desired (Drosg et al. 2015).

19.3.2 Digestate for Seed Priming

Digestate has found application in seed priming due to its elevated nutrient composition. Conventionally, seeds are pre-treated or soaked prior to planting in order to overcome the challenge of field emergence in certain seeds possessing thick seed coats (Harris et al. 2005; Paparella et al. 2015; Farooq et al. 2019). Pre-treating seeds before germination also offers the advantage of separating dead seeds as well as low-vigour seeds from viable ones prior to planting. Pre-soaking seeds in such nutrient-rich slurry as digestate would offer the added advantage of incorporating nutrients onto the seeds. This was found to enhance seed germination and seedling growth (Feng et al. 2011; Zhao et al. 2014). Soluble nutrients in the digestate are absorbed by the seeds via osmosis, and this effectively activates the enzyme source in seed embryos and endosperm in addition to accelerating nutrient transformation, promotion of metabolism and protection against pathogens (Feng et al. 2011).

19.3.3 Digestate as Fungicide

Chemical fungicides have been used as a common method of protecting plants against fungal phytopathogens among SH farmers. Long-term use of these chemical agents may result in several challenges due to their hazardous effects, which include residence time in the environment and acquisition of resistance by pathogens (Mukherjee et al. 2016). Moreover, the adverse effect of chemical fungicides on biodiversity due to surface water runoff and leaching propels the need to identify different types of fungicides that are efficient and environmentally friendly. The application of digestate for the control of phytopathogens is a viable approach to the management of pathogens on farmlands as digestate has been observed as a biocontrol agent that inhibits the proliferation of phytopathogenic fungi (Feng et al. 2011; Baştabak and Koçar 2020). A report by Pan et al. (2018) presented the antagonistic effects of digestate on phytopathogenic fungi, *Alternaria solani* which causes the potato blight disease (*Phytophthora infestans*). Further laboratory investigations have ascertained the inhibition of several phytopathogenic fungi, *Rhizoctonia cerealis*, *Fusarium oxysporum*, *Rhizoctonia solani*, *Bipolaris sorokinianum*, and *Sclerotinia sclerotiorum*, by the utilization of digestate (Tao et al. 2014). Application of liquid portion of digestate significantly inhibited the growth of the above-mentioned phytopathogenic fungi. Biocontrol of parasitic nematodes affecting tomato plants is another benefit of digestate as bionematicides (Jothi et al. 2003).

19.3.4 Digestate as Soil Remediation Agent

Africa is rich in mineral resources, hence the predominance of different exploration, mining, utilization and transportation of these minerals and their finished products (Busia and Akong 2017). These processes have resulted in the introduction of pollutants to the environment leading to contamination of potential agricultural lands (Salam et al. 2018). These pollutants range from mine tailings to hydrocarbons, and the need for remediation is imperative as it will alleviate public health risks and improve agricultural as well as socioeconomic activities (Ngole-Jeme and Fantke 2017). Residency of these pollutants in the environment have resulted in decreased fertility of African soils by reducing the soil pH, which has contributed to more than 33% of SSA soils being acidic (Pauw 1994). Valorisation of digestate for the remediation of metal-polluted soil is essential since digestate has been correlated with the immobilization of metals in the soil, elevation of soil pH and promotion of soil microbial activities, thereby enhancing remediation and agricultural processes (Garcia-Sánchez et al. 2015; Peng and Pivato 2019).

Thermal pyrolysis of digestates rich in lignocellulosic materials results in the production of biochar (Mohammadi et al. 2019). Besides utilization of biochar as a soil amendment to enhance plant growth, biochar has been associated with additional applications, which includes filtration of drinking water due to its ability to remove heavy metals from aqueous solutions (Aso 2020). It also expedites the remediation of soil polluted by pesticides and organic contaminants such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) via stabilization of the organic contaminant and improvement of the decomposition of the contaminants by indigenous soil microbiota (Guo et al. 2020). Production of biochar is similarly of environmental benefit as it is a potential carbon sink (carbon sequestration) which aids in reducing our carbon footprint (McHenry 2009).

19.3.5 Digestate in Livestock Management

Utilization of densified digestate as a substitute for sawdust and wood chips for litter and bedding for poultry and cattle, respectively, is of economic benefit (Feng et al.

2011; Quintern and Morley 2017). Similarly, incorporation of bulking agents of lignocellulosic origin during composting of digestate makes the final product a suitable source of nutrition for livestock (Stoknes et al. 2013; Stoknes et al. 2016). Production of vermicast via vermicomposting of digestate for agronomic purposes is a feasible application of digestate. Besides agronomy, vermicomposting of digestate is an appropriate technique for the production of earthworms for livestock feed (Jjagwe et al. 2019). Pyrolyzed and gasified pellets of dehydrated digestate are a potential feed additive for farm animals (Wu et al. 2017; Hagemann et al. 2018). Conversion of the excess or agricultural-unsuitable digestate into pellets forms a source of carbon and energy (Al Seadi et al. 2013; Nagy et al. 2018).

Due to its elevated nutrient content, liquid digestate is also used in microalgal cultivation (Massa et al. 2017; Ayre et al. 2017; Nagarajan et al. 2019). Application of digestate as a growth medium or culture booster for the cultivation of microalgae is of immense benefit to different industries as separated microalgal biomass can also serve as animal feed (Monlau et al. 2015; Quintern and Morley 2017; Kaur et al. 2020). Algae is extensively utilized in various applications such as production of livestock feed, biodegradable packaging as well as chemical and cosmetics production, which contributes to a circular economy (Aso 2020). Despite the fact that application of digestates enhances the cultivation of microalgae, digestate with elevated NH_3 content and turbidity could limit the proliferation of algae by impeding photosynthesis (Xia and Murphy 2016). This also supports the concept of characterization of digestate prior to utilization to inform selection of the application route that will result in maximal benefits to the user.

19.3.6 Digestate in Bioprocesses

Recirculation of digestate as a feedstock for generation of additional biomethane is an effort to valorise digestates and mitigate the challenge of methane emission from undigested materials in the digestate (Monlau et al. 2015). Although, this is practiced on a large scale, SH farmers may borrow a leaf from this and recirculate digestate. In addition to mitigating the challenge of GHG emissions, recirculation of digestate as a feedstock could also serve as a means of conserving water, which is a limited resource to some SH farmers in Africa. Furthermore, production of commercially and industrially beneficial bioproducts such as bioethanol, biodiesel, hydrolytic enzymes (cellulases, proteases) and biosurfactants through solid-state fermentation of digestates is a viable option for the application of these digestates (Fuldauer et al. 2018; Cerda et al. 2019). Utilization of digestate for the production of bioproducts are economically and environmentally beneficial to SH farmers (Cheteni 2017). It has potential to alleviate poverty via creation of employment opportunities for the community. The products can also serve as eco-friendly, renewable substitutes for petroleum fuel. Fermentation of liquid digestate for the production of bioethanol is an economical and sustainable substitute for utilization of freshwater and nutrients during production of bioethanol (Gao and Li 2011; Logan and Visvanathan 2019).

Bioethanol is an extensively used biofuel globally and its effective production is attained via various metabolic processes of hydrolysis, fermentation, distillation and dehydration of digestate biomass (Cerda et al. 2019). Incorporation of digestate as a substrate for bioethanol production also limits the pre-treatment time for substrates as well as reduces the concentration of rate-limiting pentose whose accumulation obstructs the fermentation phase of bioethanol production (Teater et al. 2011; Cesaro and Belgiorno 2015).

Another bioproduct proposed is a starch-based biofilm. This biofilm incorporates valorised digestate, and it serves as a sustainable alternative to farmers to replace plastic biofilms that are conventionally used for mulching on farmlands. Solid digestate was treated by an ultrasonic thermoalkaline treatment to remove the non-functional compositions and subsequently incorporated in plasticized starch paste, which was then used to prepare mulching biofilms. The produced composite biofilm exhibited a higher tensile strength and degradation temperature as well as elastic modulus compared to pure starch-based film (Zhao et al. 2021). Production of these bioproducts may be cost-intensive to SH farmers; however, SH farmers could generate income by marketing the digestate as a resource to bioprocessing industries where it is subjected to different post treatments to enhance its applicability and environmental friendliness.

19.4 Post-Treatment of Digestate Prior to Downstream Applications

Digestate, generally used for several applications highlighted in Sect. 19.3, needs to meet hygienic, safety and quality requirements to avoid environmental and health risks as well as to improve digestate quality for storage purposes and later use (Peng and Pivato 2019; Aso 2020). Heavy metals and disease-causing microorganisms as well as impurities like plastics and glass can leach into the environment if digestate is applied without treatment (Logan and Visvanathan 2019). Additionally, unfavourable greenhouse gases (GHGs) such as carbon dioxide, nitrous oxide and methane are emitted from digestate when used untreated (Rehl and Müller 2011; Askri et al. 2016; Peng and Pivato 2019). Over-application can also lead to N and P leaching thus contaminating water bodies (Maurer and Müller 2019). The AD process partially sanitizes the digestate, especially if a thermophilic AD plant or extended HRT is used (Manyi-Loh et al. 2019). However, when stored for a long period, digestates emit GHGs and can accumulate pathogenic microbes; therefore, post-treatment is required to pasteurize and improve the quality of the digestate as well as to reduce environmental impact (Askri et al. 2016). Several digestate post-treatment methods that are applicable to SH farming systems are highlighted in the subsequent sections and summarized in Fig. 19.3.

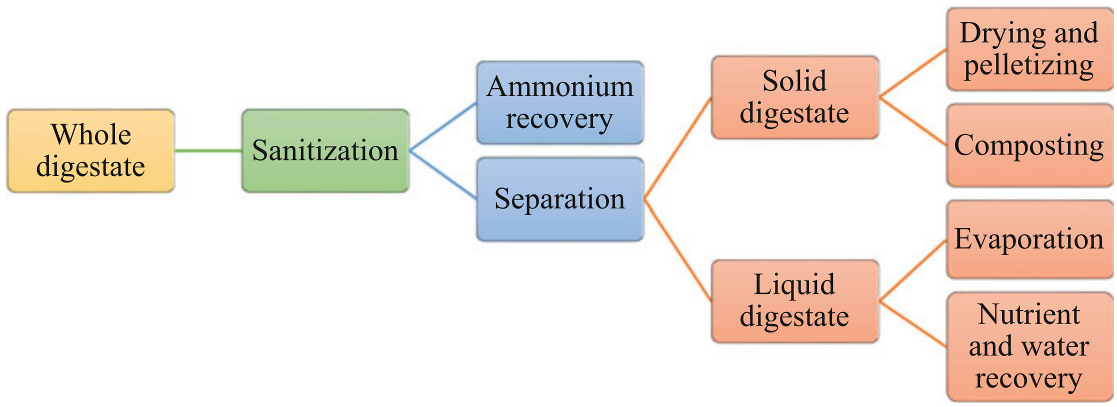

Fig. 19.3 Flow diagram for digestate post-treatment steps for smallholder farmers

19.4.1 Separation of Solid and Liquid Digestate

Whole digestate can be separated into solid and liquid fractions unless the digestate is produced from a dry AD system that contains 30–40% solids or is thickened to solid fraction using wood chips or other bulking agents (Logan and Visvanathan 2019). Generally, whole digestate that is produced from a wet digester contains less than 6% total solid content (Baştabak and Koçar 2020). Through separation, less storage space is required to store solid digestate compared to whole digestate (Lukehurst and Bywater 2015). Separation of liquid and solid digestate can be achieved through dewatering processes, for example screw-press separators that consume less energy compared to decanter centrifuges and belt presses (Møller et al. 2000; Wiśniewski et al. 2017). Alternatively, if the digester design includes a storage/overflow tank (Fig. 19.4), it is possible to collect the liquid overflow as liquid digestate and the sediment that remains as solid digestate. Designing digesters to include the overflow tank will aid in simplifying the separation process by SH farmers.

19.4.2 Sanitization of Digestate

Whole digestate should be treated for 1 hour at 70 °C in a mixing tank after removal from the digester for sanitation purposes as recommended by the European Union sanitation standard (Baştabak and Koçar 2020). A suggestion for SH farmers is to harness the heat produced by composting or by combusting a small portion of the biogas produced by the digester to sanitize the digestate through heating. If biogas is used as a source of heat, it is essential to perform a cost-benefit analysis to weigh out the benefits of using a portion of it for sanitation while producing quality digestate products for commercialization as well as to replace expensive chemical fertilizers for crop production. The evaporated water from sanitation and/or post-treatment processes can be recycled into the digester or used for irrigation purposes to reduce

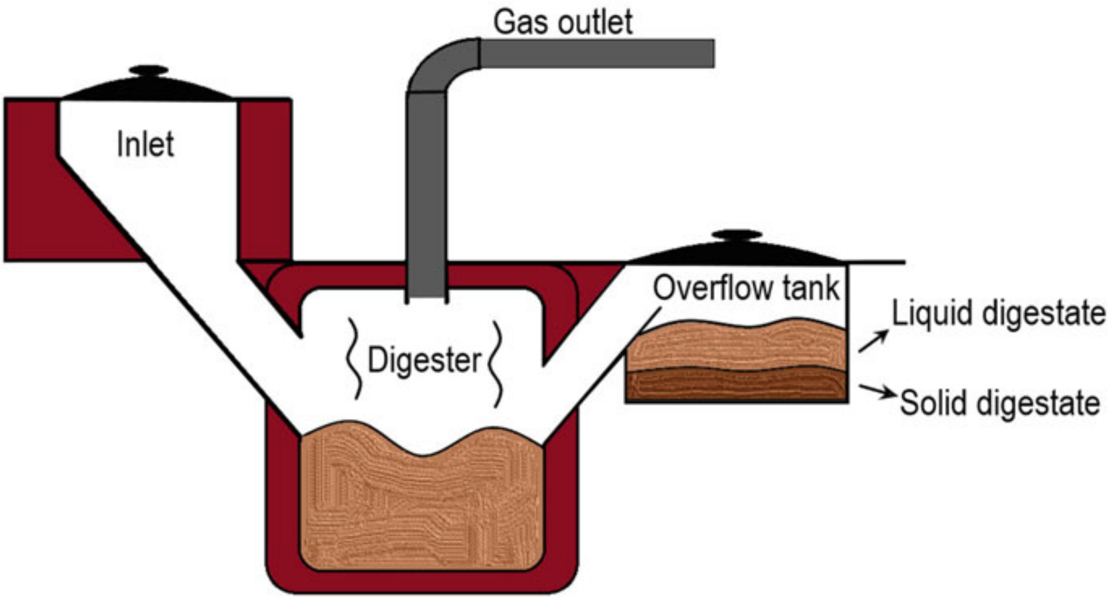

Fig. 19.4 Fixed dome digester design that includes an overflow tank (Adapted with modifications from Saleh 2012)

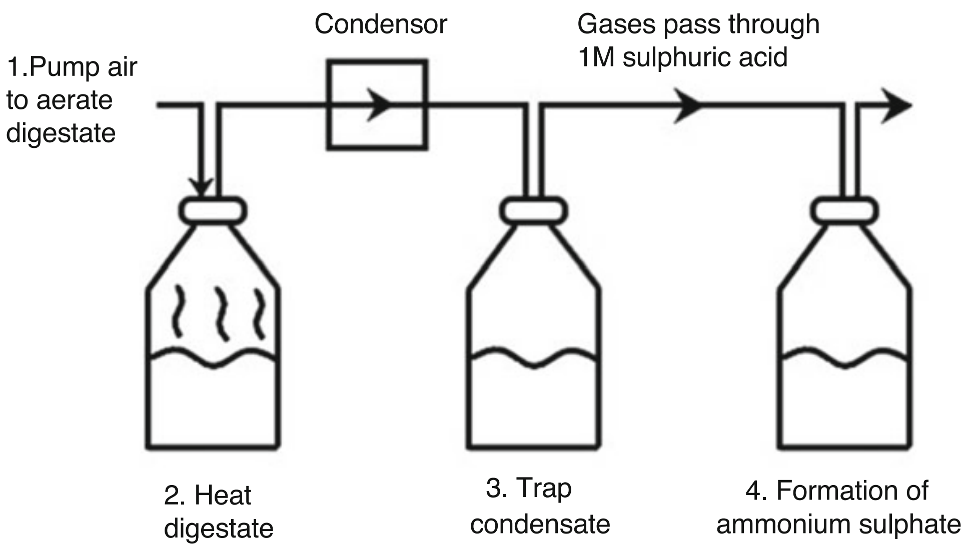

Fig. 19.5 Digestate sanitation and ammonia recovery approach (Adapted with modifications from Törnwall et al. 2017)

water requirements. A drawback to heating digestate is the loss of ammonia and mineral nitrogen in the form of nitrous oxide (a GHG) (Baştabak and Koçar 2020). As demonstrated in Fig. 19.5, high amounts of ammonia can be recovered from heated digestate by trapping the condensate for reuse and allowing the gases to pass through sulphuric acid solution to form ammonium sulphate (Törnwall et al. 2017). The ammonium sulphate can be added to dried/solid digestate, which generally contains less nitrogen content than liquid digestate (Logan and Visvanathan 2019; Manyi-Loh et al. 2019).

19.4.3 *Solid Digestate Post-Treatment*

Following separation, solid digestate must undergo post-treatment to improve its quality for downstream purposes. Some solid digestate post-treatments discussed in the following subsections include drying, pelletizing and composting.

19.4.3.1 Drying and Pelletizing Digestate

Although various methods for drying digestate exist, such as thermal, thermochemical, hydrothermal, physical and mechanical (drum-drying or belt drying) methods (Manyi-Loh et al. 2019), the biogas generated from the AD plant is an available form of energy that can be harnessed to dry solid digestate for handling and storage purposes (Maurer and Müller 2019). Solar drying is another feasible approach for SH farmers to remove moisture from unseparated or solid digestate. Solar drying involves drying out digestate in a ventilated greenhouse or open hall with turning to ensure good quality digestate is produced. Exposure to the renewable thermal energy provided by the sun enables evaporation to occur (Frischmann 2012). As previously mentioned, using the ammonia recovery approach by Törnwall et al. (2017) on the evaporated contents could prevent nitrous oxide emissions into the atmosphere while the recovered ammonia can be added to the post-treated dried digestate to enhance its quality as a fertilizer.

Pelletizing dried digestate on a large scale involves the installation of heavy machinery that requires high-energy input. Due to cost implications of such large-scale machinery and associated energy, the process is prohibitive to SH farmers. It is, therefore, suggested that small manual pellet mills are used as a viable option for SH farmers to pelletize dried digestate. Petrova et al. (2021) recommended producing larger-sized pellets for application to reduce high levels of nitrous oxides from being emitted. The pellets may be commercialized as organic fertilizers and serve as an additional source of income for SH farmers.

19.4.3.2 Composting Digestate

Composting is the most practiced form of post-treatment of solid digestate. This self-heating process involves the decomposition of OM from digestate (if possible with bulking agents) under aerated conditions. The process forms stable, nutritive and safe humus from solid digestate that can improve the soil water-holding capacity and plant growth when applied (Zeng et al. 2016; Congilosi and Aga 2021). Apart from being a source of nutrients and OM, compost also provides an essential role in supporting soil biodiversity and controlling soil-borne phytopathogenic microorganisms (Vitti et al. 2021). Moreover, composting can lower metal mobility and pathogen levels (Congilosi and Aga 2021). Composting of manure was shown to reduce ARGs in several studies (Ho et al. 2013; Qian et al. 2018; Riaz et al. 2020).

Congilosi and Aga (2021) suggested implementing composting following AD to improve ARG removal from digestate. Vu et al. (2015) suggested that passively aerated composting with digestate, bulking agents such as wood chips or straw and biochar is an efficient post-treatment that produces low amounts of GHG emissions. Rehl and Müller (2011) reported that overall solar drying and composting were the most resource-efficient post-treatment methods to use with reduced environmental impact.

19.4.4 Liquid Digestate Post-Treatment

Membrane filtration followed by reverse osmosis, aerobic biological wastewater treatment or evaporation are expensive and/or energy intensive methods that are employed to purify liquid digestate by removing the water component and concentrating nutrients for use as a fertilizer. Other methods for treatment of liquid digestate include struvite precipitation, ammonia stripping, activated sludge treatment, UV irradiation, ozone treatment, chemical coagulation, electrocoagulation, flocculation and microalgal cultivation (Manyi-Loh et al. 2019). Similarly, to the treatment of solid digestate, it is suggested that liquid digestate is exposed to the heat derived by biogas combustion to evaporate the moisture and concentrate the nutrients. Smallholder farmers can commercialize the concentrated nutrients as a fertilizer product or intermittently apply diluted forms to their own farms for crop production. The recycled water can be mixed with cow dung and added to digester systems in place of freshwater or be used for irrigation purposes. This is of particular importance to SH farmers in areas where periodic water scarcity is experienced or excessive labour is required for water collection.

19.5 Recommendations

The utilization of digestate offers the possibility to recycle nutrients from organic waste materials back to the food chain. Thus, recommendations to SH farmers are as follows:

- In cases where SH farmers are faced with on-farm factors such as nutrient-deficient soils and pests, digestate can be used in their gardens as organic fertilizers and biopesticides, respectively.
- Digestate can also be used for seed priming to improve crop growth and quality.
- On SH farms that rear livestock, digestate can be used as animal bedding, for aquaculture and algae production.
- On occasions where SH farmers do not have sufficient water supply, the liquid digestate can be used for irrigation purposes.

- Finally, on SH farms that have sufficient income to invest in newer technologies, digestate can be utilized in several bioprocesses to generate high-value products such as biofuels. Alternatively, digestate can be sold to industries with the necessary facilities to produce such bioproducts.

Overall, the array of digestate applications that are available enable SH farmers to appropriately select the application that is relevant to their respective farms based on their needs and available facilities. Moreover, the variety of digestate applications available to farmers ensures that digestate management is simplified since farmers can explore several applications and in so doing create new digestate product markets with concomitant financial gain. Appropriate valorisation of all the resulting digestate from the AD process has the additional benefit of ensuring environmental sustainability of the AD process as it will prevent digestate disposal with associated negative environmental implications. That being said, the appropriate post-treatment of the digestate, which is closely linked to the choice of digestate application, is necessary to valorise digestate in an eco-friendly manner.

Digestate can be separated into two components (liquid and solid) that requires separate storage. Separation is normally done to reduce the volume requiring storage or for increasing income generation as solid and liquid digestate can be sold as separate products. For SH farmers, it is recommended that:

- Low-cost separation methods such as simple sedimentation/filtration be adopted.
- The solid digestate should be composted to reduce GHG emissions.
- The liquid digestate can be further concentrated to increase nutrient content by evaporating moisture through heat generated by biogas combustion.

Thereafter, both solid and liquid digestates can be commercialized for income generation or used for several applications.

19.6 Conclusion

The current chapter demonstrates the use of digestate as an organic fertilizer for improved agricultural production. In addition to digestate use as a fertilizer, digestate could be key to SH farmers widening their agricultural practices by expanding its use for pest control, aquaculture, livestock management, seed priming, soil remediation and renewable energy generation. This could aid in income generation, promoting holistic farming and moving from subsistence to commercial farming. The variability of digestate with respect to physical, chemical and biological properties (e.g. dry matter, C/N ratio, pH, nutrients and beneficial microbes) has been highlighted in this chapter. It is worth mentioning that the physico-chemical properties and efficacy of digestate depends on the nature of the feedstock utilized, storage method and handling as well as method of application.

For future research, studies should look into the association between feedstock type and the agronomic properties of digestate. Such awareness will permit informed selection of feedstock that can result in digestates with specific properties, which make it desirable for the intended downstream application. Identification of biological content such as beneficial and pathogenic microbes as indicators of digestate quality could also be useful for digestate product characterization. Overall, the digestate market in Africa is still undeveloped, coupled with its general knowledge for application. However, with increased AD adoption, digestate regulations could also grow, especially in countries such as South Africa, Uganda and Ethiopia, where AD studies have already been conducted for both digestate and renewable energy production. With the drive towards holistic farming and the shift in perspective of AD from 'biogas optimization' to 'integrated biogas–digestate optimization' it is anticipated that future research trends will be directed towards maximising benefits associated with digestate use. Maximising appropriate digestate use, particularly by SH farmers, based on scientific evidence and informed guidance would in turn qualify this valuable resource being termed 'liquid gold'.

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