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Enhancing Water and Food Security Through Improved Agricultural Water Productivity

New Knowledge, Innovations and Applications

Springer

Chapter 5
Application of Endophytes in Bioremediation, Biotransformation, and Water Disinfection for Irrigation Systems

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Abstract Globally, freshwater is insufficiently distributed to meet all present and future water demands. As a result, agricultural water demands must be satisfied by creative methods such as wastewater treatment and recycling. Several physical and chemical remediation procedures have been utilised to degrade or remove environmental pollutants in wastewater. Some techniques produce toxic metabolites, are ecologically unfriendly and expensive, or entail the relocation of contaminants rather than reducing them. It is, therefore, critical to incorporate biological approaches that use organisms' metabolic activities to break down or change toxic contaminants into less dangerous intermediates or products. Employing plant symbiont microorganisms known as endophytes has been shown as a sustainable and eco-friendly approach for decontaminating water and enhancing agricultural output. In this chapter, we highlight the potential of endophytes as wastewater bioremediation, biotransformation, and disinfection agents.

Keywords Agricultural product · Endophytes · Irrigation · Wastewater · Eco-friendliness

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T. Mabhaudhi et al. (eds.), *Enhancing Water and Food Security Through Improved Agricultural Water Productivity*,
https://doi.org/10.1007/978-981-96-1848-4_5

5.1 Introduction

Agriculture water demand is hardly met, relying solely on rainfall and soil water accessible to the root capillarity. It is common knowledge that sustainable agricultural practices face problems of water shortages and inefficient irrigation water systems in most parts of the world. The current climate change and adverse weather events are exacerbating the situation, affecting virtually all regions of our planet. Irrigation is an essential strategy for addressing the world's growing food insecurity. It provides a reliable water supply to sustain agricultural farms, and almost one-half of the available irrigation water is supplied from groundwater originating from shallow and deep-water tables (He et al. 2020a, b). Ground and surface water are the largest and most important sources of freshwater for irrigation (Siebert 2010). While available freshwater is sufficient to meet all current and future water demands, its spatial and temporal distributions are insufficient.

Many regions, particularly the arid and semi-arid regions, such as South Africa, have inadequate water resources to meet requirements (Mengistu et al. 2021). In these water-scarce areas, the reuse of domestic wastewater (DWW) (e.g., artificial ponds from surface runoff) for irrigation is a reasonable alternative agriculture practice to achieve sustainable water management (Patience et al. 2021; Phakathi et al. 2021). In all these regions of the earth with shallow levels of rainfall, there is little available quality water to support human and plant activities due to low levels of precipitation and high rate of evapotranspiration coupled with prolonged dry periods and extreme weather conditions (Bortolini et al. 2018).

Reports and literature reviews originating in the countries on the quality of various aquatic sources in recent decades suggest the presence of inorganic (Agunbiade and Moodley 2014; Rimayi et al. 2018; Gani et al. 2021), organic (Vasseghian et al. 2021), and biological (Verlicchi and Grillini 2020) contaminants including water used for irrigation of crops. Often, these contaminants occur in effluents from anthropogenic sources such as domestic sewage, wastewater treatment plants, agricultural land use, and industrial and mining operations, which may be discharged into the water system through numerous paths. Using irrigation water containing even small amounts of these pollutants puts biodiversity, consumer health, and food quality in danger immediately and over time. These dangers include but are not limited to food poisoning, spoilage and wastage, malnutrition, infertility, stillbirths, decreased effectiveness of antibiotics, loss of agricultural products, rejection of products for export abroad, and even human and animal fatalities.

Moreover, numerous studies have listed various physical (like filtration) and chemical (such as nanoparticles, charcoal) techniques that can be used to clean wastewater for agricultural use; however, there are few studies of a similar nature describing biological methods, particularly the employment of endophytic microbes in irrigation water purification. This chapter focuses on the biological application of endophyte as a tool for bioremediation, biotransformation, and water disinfection for irrigation systems. Plants have symbionts called endophytes; these microbes confer growth benefits to the plant host by mediating activities such as nitrogen fixation, phosphate solubilization, and biological control of plant diseases (Raimi and Adeleke 2021). Numerous studies have shown that endophytes can sweep up, detoxify, and even destroy pollutants in wastewater. Therefore, we postulate that employing these isolates alone or combined to clean irrigation water would boost farm product output, safety and quality.

5.2 Application of Endophytes in Bioremediation of Contaminated Aqueous System

The dawn of microbial biotechnology has established the beneficial functions of endophytes in different sectors, such as agriculture, medicine, and industry (Fig. 5.1). The application of endophytes for environmental remediation of pollutants cannot be overemphasized due to their efficiency, eco-friendliness, and sustainability. Their ability to degrade complex organic compounds makes them significant in the bioremediation of contaminated aqueous environments. Endophytes are endosymbionts, often bacteria or fungi, that exist in the internal tissues of healthy plants (Raimi and Adeleke 2021). Endophytes have been employed in beneficial metabolic activities, from improving plant growth and development to producing bioactive and/or metabolic substances of medicinal and ecological importance (Fadiji and Babalola 2020). They are ubiquitous, and different plant-associated endophytes have been linked with critical biological processes such as biocontrol

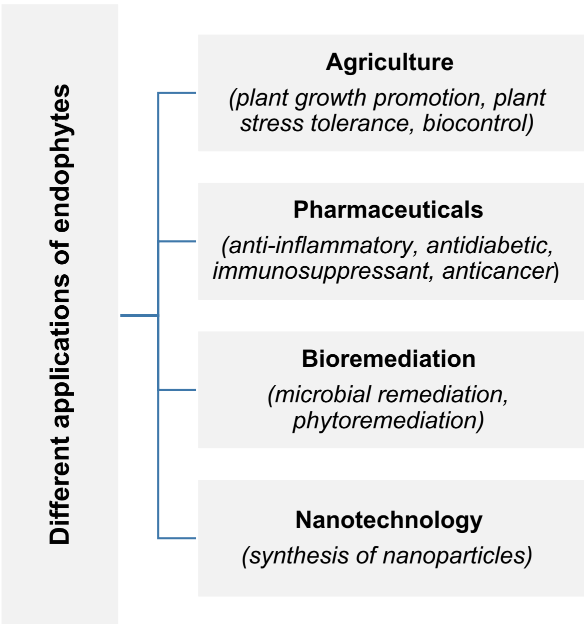

Fig. 5.1 Beneficial applications of endophytes

and bioremediation (Rodriguez et al. 2009; Anyasi and Atagana 2019). This is due to their potential to produce active intermediates or products by altering complex compounds to less-toxic counterparts (Wang and Dai 2011).

Different physical and chemical remediation techniques have been used to degrade or remove environmental pollutants. Some of these techniques are toxic metabolite producers, environmentally unfriendly, cost-intensive, or involve the relocation of contaminants instead of degrading them (Chlebek and Hupert-Kocurek 2019; Khan et al. 2019). Incorporating biological techniques that utilize the metabolic functions of organisms to degrade or transform these toxic pollutants into less harmful intermediates or products is imperative (Akhtar and Mannan, 2020). Such techniques, including bioremediation with endophytic microorganisms, have been recorded as sustainable and eco-friendly means of environmental decontamination (Singh et al. 2020). Production of relevant biological compounds by endophytes enhances their application as a bioremediation agent for contaminated aquatic ecosystems.

Contaminated aquatic systems refer to bodies of water contaminated by various pollutants, leading to detrimental effects on the ecosystem and potentially endangering human health. Contamination of aquatic systems could be due to natural disasters or anthropogenic activities. The discharge from mining, petrochemical, and textile or dye industries comprises harmful substances that present a health risk to humans. Notably, soil and water often exhibit a significant accumulation of heavy metals at high concentrations (Saravanan 2021). The preservation and restoration of these ecosystems are crucial for maintaining the health and sustainability of our water resources. Furthermore, aquatic ecosystems such as wetlands are potential water sources for economic purposes; however, these ecosystems are usually contaminated with different pollutants from anthropogenic sources.

These pollutants include agrochemicals, petroleum hydrocarbons as well as halogenated solvents. Contamination or pollution of the aquatic ecosystem is severe and poses some threats to the environment; this comprises possible absorption of heavy metals by aquatic organisms and seepage of recalcitrant and toxic pollutants into the underlying groundwater (Kumar and Dwivedi 2021). Heavy metals and hydrocarbons in the surface or groundwater are of grave concern as many are human carcinogens that can adversely affect some physical and metabolic processes in plants (Hussain et al. 2018; Anitha 2022). Developmental strategies to mitigate the environmental effects of these pollutants are essential, hence the incorporation of different types of bioremediations with endophytic entities. Bioremediation with endophytes encompasses remediation with biological entities such as microbial remediation and phytoremediation. Endophytic microorganisms, encompassing bacteria, fungi, and archaea (Fig. 5.2), are known to engage in symbiotic associations with various plant components and protect the plants against different environmental stresses (Govindasamy et al. 2018).

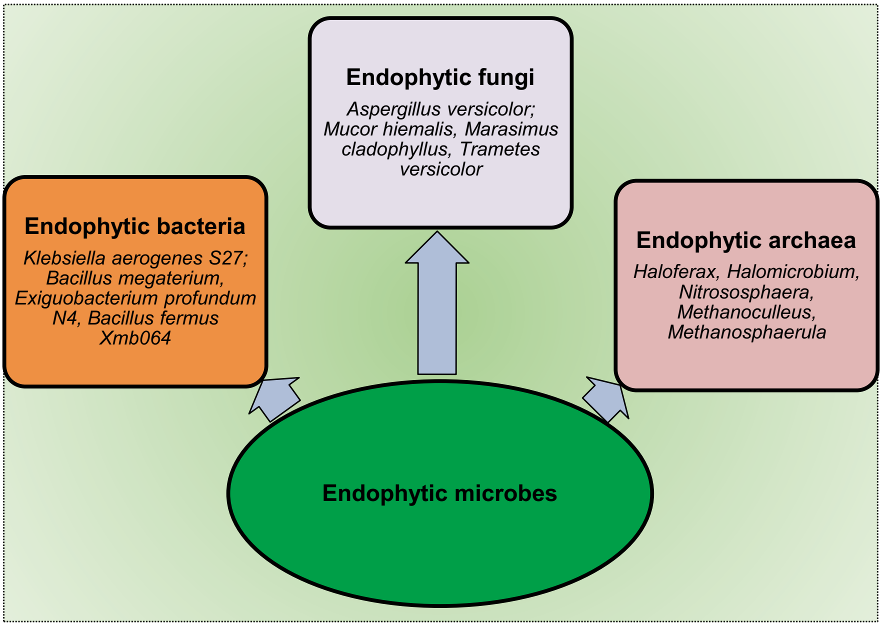

Fig. 5.2 Endophytic microbes used in bioremediation of aqueous systems

5.3 Application of Endophytic Microbes in the Decontamination of Aquatic Systems

5.3.1 Bacterial Endophytes as Remediation Agents for Aquatic Systems

Bacteria are effective biodegradation and bioremediation agents due to their ubiquity and versatility. Given the right conditions, bacteria have few universal toxins, making it likely that they can break down any given substrate. Bacteria-mediated processes have been employed to reduce the toxicity of environmental contaminants such as heavy metals. Heavy metal stress can be more easily tolerated and treated by endophytic bacteria as biodegradation, particularly in live cells, is the primary elimination route for endophytic bacteria (Sim et al. 2019). Removal of environmental pollutants by bacterial endophytic entities is essential and promising. The ability of these bacterial strains to reduce heavy metals concentration in plant species and enhance plant growth was demonstrated by Ali et al. (2017).

Metals are more readily available to plants, thanks to endophytic bacteria, which facilitate their movement through plant tissues. The potential of endophytic bacteria *Klebsiella aerogenes* S27 to completely decolorize a carcinogenic chemical, malachite green (MG), in wastewater was examined by Shang et al. (2019), where the endophyte facilitated transformation via actions of novel enzymatic oxidoreductase

KaTMR to transform malachite green into less-toxic metabolites. Bacterial endophytes have been implicated in removing xenobiotics from contaminated water (Ho et al. 2012). Detoxification of the agrochemical atrazine, which is a known contaminant of surface and groundwater by endophytic bacteria Streptomyces was explored by Mesquini et al. (2015). *Bacillus megaterium* has also been employed to degrade and detoxify a significant portion of agrochemicals (Liu et al. 2014). Endophytes utilize the enzyme organophosphorus hydrolase to degrade agrochemicals (Barman et al. 2014).

Azo dyes are stable xenobiotics due to their stable molecular structures, and endophytes are potential purifiers of effluents from the dye (Shang et al. 2019). *Exiguobacterium profundum* strain N4 converts the diazo dye Reactive Black 5 to less hazardous benzene and phenanthrene via enzymatic oxidation, reduction, desulphonation, and demethylation (Sharma and Roy 2015; Karaś et al. 2021). Reduction in the cytogenetic effect of DB-14 dye due to transformation by the alkaliphilic endophytic bacteria *Bacillus fermus* strain Xmb064 was observed in the study of Sandesh et al. (2019). Absolute degradation of the DB-14 dye was observed after four days of aerobic incubation at 37 °C with the aforementioned endophytic bacteria. Also, in a study by Hussain et al. (2018), 20 strains of endophytic bacteria isolated from the roots and shoots of *Typha domingensis* and *Pistia stratiotes* exhibited credible potential in biodegrading heavily contaminated textile effluent. All the bacterial test strains showcased significant reduction in the chemical and biological oxygen demand, coloration intensity, toxicity level, organic nutrients, and heavy metals.

A study by Ijaz et al. (2015) showed the efficiency of a relatively recent technique, floating treatment wetlands (FTWs). The technique involves the cultivation of plants on buoyant mats without soil. In this setup, the submerged plant biomass freely hangs in the water column beneath the mat. This innovative approach, characterized by its simplicity and easy establishment used with a pollutant-degrading endophytic bacteria, has been reported to be highly effective in enhancing sewage effluent quality. The introduced endophytes exhibited a significant level of colonization in both the root and shoot of the plants, as well as in the wastewater itself (Ijaz et al. 2015).

5.3.2 Endophytes as Mycoremediation Agents for Aquatic Systems

Fungi are known for rapid growth, quick adaptability, and accumulation of high concentrations of heavy metals in water environments when compared with bacteria. They remediate polluted aquatic ecosystems through bioaccumulation, biomineralization, and adsorption of the available pollutants (Dang et al. 2018; Kumar and Dwivedi 2021). Using fungal entities to remediate or rid the polluted aquatic ecosystems of contaminants is called mycoremediation. A possible means of responding to heavy metal stress by endophytes is through the production of a defence mechanism known as extracellular polymeric substances (EPS), which binds/immobilizes heavy metal ions. These secreted EPS play a critical role in enhancing the heavy metal tolerance ability of most endophytes at different concentrations of several heavy metals (Dang et al. 2018). Endophytic fungi (EF) are abundant in plants and can display their high metal tolerance capacity by proliferating in a heavy metal-polluted environment (Mohammadian et al. 2017). Different EF have been employed in different mycoremediation strategies, and most of them have demonstrated their pollutant remediation strategies through enzymatic detoxification, degradation, filtration, immobilization, etc. (Kumar and Dwivedi 2021). Mycoremediation of hydrocarbons contaminated aquatic ecosystem by the EF *Pleurotus ostreatus* exhibited the ability of the ligninolytic enzyme, manganese peroxidase, in breaking down polycyclic aromatic hydrocarbons (PAHs) (Arfaeinia et al. 2019).

Mycoremediation of agrochemicals such as glyphosate, paraquat, endosulfan, and aldrin is an efficient and environmentally friendly means of remediating agrochemical-contaminated water as some conventional methods will either incur cost or generate toxic intermediates (Eman et al. 2013). Degradation of environmental contaminants such as agrochemicals has been demonstrated by the characteristic ability of the EF, *Trametes versicolor* (Bhadouria et al. 2020). *Trametes versicolor* portrayed its fast adsorptive and, subsequently, high degradation ability on hydrophobic synthetic pesticides, chlorpyrifos, dicofol, and cypermethrin, according to Hu et al. (2020). Several studies have demonstrated the degradation capacities of EF in removing agrochemicals from wastewater. Amongst the different fungi analyzed for their potential to metabolize the herbicide Granstar (tribenuron-methyl), *Aspergillus versicolor* exhibited a higher ability to degrade tribenuron-methyl to different metabolites within 35 days of study (AI-Jawhari and AI-Sead 2016).

Pharmaceuticals are one of the most common xenobiotics in wastewater, surface, and groundwater. This threatens public health, hence the need for their removal. The study of Esterhuizen-Londt et al. (2016) investigated the potential of the EF *Mucor hiemalis* to take up and degrade acetaminophen in wastewater. They also observed the ability of the fungi to exhibit no oxidative stress that could have resulted from exposure to acetaminophen; the bioremediation process produced no harmful metabolites. Another EF identified in the mycoremediation of pharmaceuticals, including opiates and nonsteroidal anti-inflammatory drugs (NSAIDs), is *Trametes versicolor* (Marco-Urrea et al. 2010; Asif et al. 2017). Using their ligninolytic enzymes, *T. versicolor* has likewise been employed in the degradation of antibiotics component of pharmaceutical effluents, and the fungal entity is known to be effective in the degradation of antibiotics such as ciprofloxacin, ofloxacin, and sulfamethazine (Prieto et al. 2011; García-Galán et al. 2011). Degradation of ofloxacin and norfloxacin using the manganese peroxidase enzymes of the EF *Irpex lacteus* has also been reported (Čvančarová et al. 2015). The nonspecificity of the ligninolytic enzymes of EF enhances their ability to degrade different xenobiotics in contaminated water. These enzymes include laccases, peroxidases, catalases, hydrolases, proteases, pectinases, amylases, phosphatases, lipases, cellulases, and tyrosinases (Yang et al. 2017; Rana 2019; Choudhary et al. 2021).

Endophytic fungi have been known to be efficient bioremediation due to the nongeneration of toxic intermediates during degradation. They have been utilized in the mycoremediation of various wastewater contaminants, including synthetic dyes. The studies by Ngieng et al. (2013) and Yang et al. (2017) evaluated the degradation ability of *Marasmius cladophyllus* and *T. versicolor* concerning different synthetic dyes. They observed the potential of the aforementioned fungal entities to break down these dyes using their ligninolytic enzymes to generate no toxic by-products. Triphenylmethane is a component of effluents from textile industries. Gao et al. (2020) demonstrated that the EF *Bjerkandera adusta* possesses the capability to efficiently degrade a high molecular weight dye, triphenylmethane, through the oxidation pathway using enzymes such as manganese peroxidase and lignin peroxidase.

Endophytes naturally produce a surface-active protein compound, hydrophobins, which enhances the solubility of hydrophobic compounds and subsequently improves bioavailability and possible biodegradation by prospective enzymes (Kulkarni et al. 2017). Endophytes, especially endophytic fungi (EF), secrete an extensive range of extracellular enzymes which catalyze different metabolic activities, including the degradation of low-molecular-weight and high-molecular-weight hydrocarbons (Akhtar and Mannan 2020; Bhadra et al. 2022). Several endophytes have been portrayed in the degradation of hydrocarbons, including the degradation of long chain hydrocarbons and BTEX by EF Aspergillus and Mucor, as well as exploiting the degradation potential of different species of Fusarium in degrading different hydrocarbons have also been exploited (Asemoloye et al. 2020; AI-Jawhari 2022). These fungi are also capable of producing active substances such as cis-4-acetoxyoxymellein and 8-deoxy-6-hydroxy-cis-4-acetoxyoxymellein which have been employed in algicidal activities of eradicating toxic algal blooms from wastewater. These fungi utilize the active substances to degrade the algal cells' nuclear membrane, leading to possible algal cell deaths (Hussain et al. 2015).

Mycofiltration, a form of mycoremediation, is an eco-friendly wastewater treatment technique that utilizes the filtration abilities of the mycelium of certain fungal entities to capture and degrade environmental contaminants in water (Mnkandla and Otomo 2021). Different studies have reported on the high biosorptive capacity of EF as an efficient strategy for eradicating heavy metals in the environment. The potential of fungal mycelia to filter and improve water quality in a built ecosystem for fish culture was investigated by Chandra et al. (2022). Their study suggested the capacity of fungal mycelium to take up heavy metals, degrade contaminants, and significantly reduce coliform bacteria's microbial load in the built ecosystem. A significant reduction in assayed content of heavy metals (Pb, Zn, Fe, Cu) was observed as the concentration of these metals was within the acceptable range for the proliferation of aquatic organisms.

The study by Pini and Geddes (2020) also portrayed the feasibility of mycofiltration in remediating biological contaminants in water. They exploited the mycelia of *Pleurotus ostreatus* to trap and degrade *E. coli* in river water. *E. coli* are pathogenic fecal coliform that is of public health concern hence the need for their removal from the environment. Besides the removal of biotic pathogens like *E. coli*, *Pleurotus ostreatus* has been employed in the removal of abiotic environmental contaminants such as hydrocarbons, heavy metals, and polychlorinated biphenyls (PCBs) (Kumar and Dwivedi 2021).

5.3.3 Endophytic Archaea in the Remediation of Aquatic Systems

Endophytes are traditionally recognized as bacteria or fungi; however, recent classification has expanded to include archaea as endophytes. Notably, archaeal phyla such as Thaumarchaeota, Crenarchaeota, and Euryarchaeota have been identified in this role. Endophytic archaeal genera encompass a variety of species, including Methanoculleus, Thermoplasma, Methanococcus, Methanosphaerula, Methanospirillum, Nitrosopumilus, Nitrososphaera, Halomicrobium, Halogeometricum, Haloferax, Thermoplasma, and more (Fadiji et al. 2020). The understanding of these archaea's distribution, significance, function, and activity in relation to their host plants is still speculative, as mentioned by Müller et al. (2015). Not many studies have been conducted on the potential of endophytic archaea to decontaminate aquatic systems (Chow et al. 2022); however, the plant-growth-promoting abilities of endophytic archaea cannot be overemphasized.

Endophytic archaea play a vital role in sustainable agriculture as they possess specific genes that facilitate various plant metabolic functions, including nutrient cycling, siderophore production, and modulation of plant hormones. Moreover, endophytic archaea augment the plants' capacity to withstand and endure abiotic stress (Jung et al. 2020; Chow et al. 2022). Although susceptible to salinity, endophytic archaea have exhibited resilience to water salinity and have been found to promote the growth of certain plants, such as *Phragmites australis*, which is utilized in phytoremediation efforts (Llirós et al. 2014; Wang et al. 2022). *Phragmites australis* is a macrophyte renowned for its remarkable ability to accumulate contaminants in aquatic systems (Ahmad et al. 2014). AI-Homaidan et al. (2020) evaluated the capacity of *Phragmites australis* in wetlands to sequester heavy metals and reported significant accumulation of Zn, Cd, and Pb. A study by A. Bello et al. (2018) demonstrated that *Phragmites australis* achieved removal rates of 93%, 84%, and 95% for Cd, Ni, and Pb, respectively, over 6 weeks. Archaea's adaptation to extreme environments positions them as promising candidates for bioremediation of chemical pollutants. Various archaea species have been effectively utilized in remediating polluted locations, including acid mine drainage, hypersaline environments, and gas and oil production wastewater. For instance, the archaea, Haloarcula EH4 demonstrated significant potential in degrading aromatic hydrocarbons (Bertrand et al. 1990; Tapilatu et al. 2010; Naitam and Kaushik 2021). The utilization of endophytic archaea holds promise as a distinctive approach to minimizing environmental harm caused by contaminated aquatic systems. These archaea have the potential to provide unique solutions toward this goal.

5.4 Application of Endophytes in Biotransformation of Contaminants in Aquatic Systems

Modifying organic and inorganic contaminants from an aqueous environment via potential biotransformation by endophytes is an emerging study area. Limited studies have been conducted on biotransformation as a remedial technique as well as the biotransformation potential of endophytes (Chalifour et al. 2021; Choudhary et al. 2021; Desiante et al. 2021). Biotransformation aims to remove environmental pollutants from aqueous environments via structural and functional modification of their harmfulness, bioavailability, and persistence of chemical compounds in a biological system. It transforms chemical compounds into less toxic products via stereo selection and bio-oxidation (Huang 2022). Using endophytic microbes as biological catalysts is a microbial transformation technique (biotransformation) that aims to mitigate the challenges associated with using conventional catalysts to transform environmental pollutants. Exploration of endophytic entities for their potential to produce nonspecific ligninolytic enzymes capable of cleaving strong molecular bonds is necessary. Different endophytic microbes have been employed in the biotransformation of several contaminants, and they include Serratia, Ochrobactrum, Enterobacter, Pseudomonas, Bacillus, Aspergillus, Sphingomonas, and Cellulosimicrobium (Kuźniar et al. 2019).

An economical and efficient means commonly used in removing heavy metals from the contaminated aqueous environment is biosorption; this involves the adsorption of heavy metal ions onto the active sites of biosorbents. Examples of biosorbents include bacteria, fungi, algae, biopolymers, and plant residues (Beni and Esmaeili 2020). Endophytic fungi like Aspergillus and Penicillium are known for their high biosorbent abilities, as they can adsorb heavy metals from a contaminated aqueous environment (Ahmad et al. 2006; AI-Jawhari 2022). The extensive heavy metals adsorption capacity of the EF, *Portulaca* sp., stems from its high mycelia-producing ability (Kapahi and Sachdeva 2017). The biosorption potential of *Phanerochaete chrysosporium* to remove heavy metals from an aqueous solution was also evaluated by Rudakiya et al. (2018). They deduced that *Phanerochaete chrysosporium* utilized its hyphal cells to absorb/eradicate metals like Cd, Cu, Cr, Pb, Ni, Zn, Co, Se, and Al by binding them to their cell wall component, whereas some fungi also utilize the metals above for their metabolic activities.

Endophytes have been recognized as essential factors that enhance the removal rate of potential aqueous contaminants. Besides their increased stereoselectivity, chemoselectivity, and regioselectivity, the evaluation of EF as a biotransformation agent is due to their ability to utilize less organic solvent during the transformation process and produce little or no toxic by-products (Ekiz et al. 2018). This results in their classification as an eco-friendly, sustainable, renewable, and economical means of removing environmental contaminants from an aqueous environment (Choudhary et al. 2021). The generation of specific products during biotransformation by EF results from their specificity and stereoselectivity characteristics, as EF produces stable enzymes with extensive application. Endophytes utilize organic contaminants for their carbon and energy requirements or co-metabolize them. Contaminants can serve as electron donors due to their ability to be oxidized. Halogen-containing compounds can equally serve as electron acceptors without oxygen to aid oxygen-limited respiration processes. For example, dehalorespiration as reductive dehalogenation or oxidative anaerobic co-metabolism is a biotransformation process (Fester et al. 2014).

Biotransformation of chemical compounds by endophytic microbes has been reported to occur via some mechanisms, which include esterification, dechlorination, dehydrogenation, deoxygenation dechlorination, demethylation, hydrolysis, aldolization, oxidation, hydroxylation, carbonylation, ketonization, deacetylation, and epoxidation (Mishra and Venkateswara Sarma 2018; Tian et al. 2021; Choudhary et al. 2021; Ma et al. 2022). Biotransformation of agrochemicals, aldrin, and dieldrin metabolites into less toxic compounds by the EF *Pleurotus ostreatus* followed the hydroxylation and epoxidation pathways according to Purnomo et al. (2017). The study of Ekiz et al. (2018) exploited the potential of EF as a biocatalyst. They studied the transformation of plant metabolites to potent active by-products by the native EF *Alternaria eureka* 1E1BL1. Biotransformation of naturally occurring toxic surface-active agents in plants, steroidal saponin by endophytes, was mediated by different transformation processes such as sugar metabolism, carbonylation, dehydrogenation, etc. (Huang 2022).

Ginsenoside Rg3 is a scarce and potential anticancer agent. Hu et al. (2020) evaluated the potential of the bacterium *Cellulosimicrobium cellulans* sp. 21 to transform low bioavailable ginsenoside Rb1 to ginsenoside Rg3 through biocatalysis and hydrolysis with insignificant derivatives. Endophytic microbes like *Enterobacter* sp., *Serratia* sp., *Ochrobactrum* sp., *Arthrobacter* sp. have also been implicated in the transformation of ginsenoside Rb1 to ginsenoside Rg3 (Tam et al. 2018). Marín et al. (2018) investigated the potential of different EF to transform petroleum hydrocarbons into less toxic intermediates/products effectively. Verticillium and Xylaria spp. exhibited over 95% hydrocarbon removal rates among the EF evaluated. The potential of endophytic bacteria, *Pseudomonas* sp., to significantly reduce the concentration of an environmental priority pollutant, phenanthrene, has been investigated. A significant reduction of 61% within three days of cultivation was observed as phenanthrene was transformed into less toxic metabolites, thereby reducing the toxicity of the polycyclic aromatic hydrocarbon (Sun et al. 2018).

5.5 Endophyte-Assisted Phytoremediation Strategies for Contaminated Aquatic Systems

Phytoremediation techniques engage the ecological ability of plants and their related microorganisms, such as endophytic microbes, to essentially enhance the removal of contaminants from the environment (Riskuwa-Shehu and Ismail 2018;

He et al. 2020a). Aquatic plants can actively and passively absorb substantial amounts of metals from contaminated water and/or sediment through their roots, stems, and leaves. As a result, these plants are suited for changes brought on by heavy metals in the aquatic environment (Bai et al. 2018). Endophyte-assisted phytoremediation has been noted as a promising approach for in situ remediation of polluted soils (Fig. 5.3) due to the abundance of endophytes that have been proven to be resistant to heavy metals and/or capable of decomposing organic pollutants (Li et al. 2012). Phytoremediation of contaminated aqueous environment follows different physiological and mechanical means of interaction or mechanisms of action, which include phytostabilization, phytovolatilization, phytoextraction, bioaccumulation, chelation, degradation, and translocation (Kafle et al. 2022). Utilizing the abilities mentioned earlier of plants and endophytes is sustainable for detoxifying a contaminated aqueous environment. With the help of metal-tolerant plant species, heavy metals can be immobilized underground and made less bioavailable through phytostabilization. This prevents the metals from migrating into the ecosystem and lowers the risk of getting into the food chain (Marques et al. 2009).

Degradation genes and PGP properties are known to be present in endophytes, which improves the efficacy of phytoremediation and helps their host plant resist

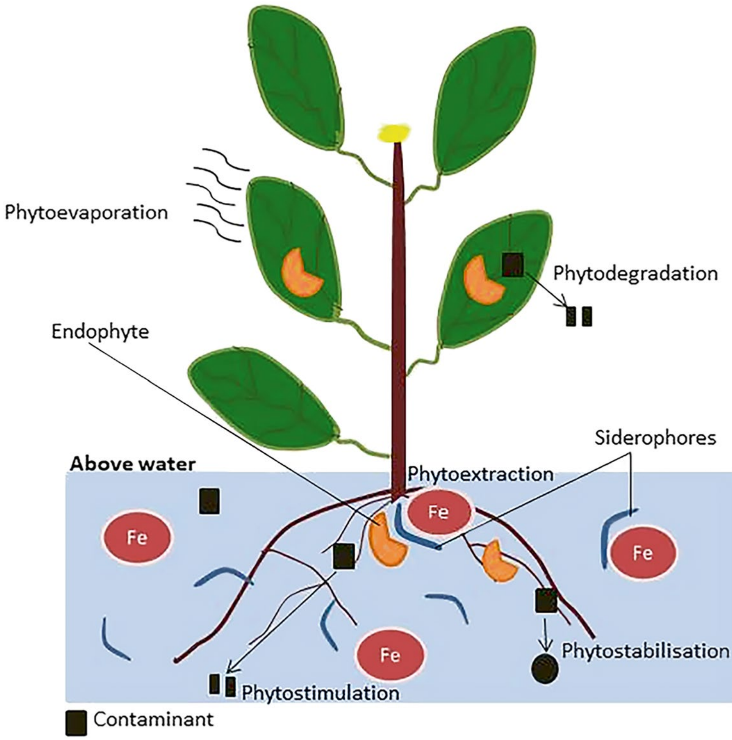

Fig. 5.3 Illustration of some endophyte-assisted phytoremediation strategies for contaminated aquatic systems

environmental challenges. Once inside the plants, endophytes can improve metal translocation and/or contribute to detoxifying organic toxins, perhaps leading to a long-term solution for mixed contaminations (Syranidou et al. 2016). Through the volatilization process, plants absorb specific compounds, such as volatile organic compounds, from the contaminated aquatic systems, convert less volatile compounds into more volatile forms, and release the contaminants into the atmosphere through evapotranspiration.

Phytoextraction involves the removal of contaminants from water or soil using plants. The role of endophytes in the phytoremediation of environmental pollutants is due to their ability to produce siderophores, which are low-molecular-weight compounds with a high affinity for metals. These siderophores aid the phytoextraction of metal ions from a contaminated aqueous environment (He et al. 2020b). Endophytes' metal tolerance mechanisms include precipitation, sequestration, compartmentation, and volatilization (Mishra and Venkateswara Sarma 2018). Endophytes protect plants from the toxic effects of the possible accumulation of excess contaminants. This accumulation process occurs in combination with the root hairs of the plants, and it is more efficient than utilizing each separately (Choppala et al. 2014; Sharma et al. 2018). The EF *Exophiala pisciphila* can accumulate significant Pb and Cd during phytoremediation (Zhang et al. 2008). Immobilization of metalloids and metals in the environment is another characteristic of EF, and plant-endophyte is a helpful process as endophytes support the plant in the secretion of secondary metabolites (Ho et al. 2012). An investigation by Sauvêtre et al. (2018) observed the potential of EF *Rhizobium radiobacter* and *Chryseobacterium nitroreducens* via plant–endophyte interaction to enhance the removal of a prominent aqueous pollutant of pharmaceutical origin, carbamazepine (CBZ). Phytoremediation of metal contaminants with some endophytic fungal isolates showed a high tolerance to heavy metals in the environment, including Cu, Pb, Zn, and Cd.

Textile dyes are water-soluble, including pharmaceuticals and paper wastes; this characteristic enables their penetration and possible contamination of groundwater if and when disposed of indiscriminately (Lellis et al. 2019; Karaś et al. 2021). Removal or detoxifying contaminants in groundwater or wastewater via sustainable and economical means such as phytoremediation is imperative. Endophytes remediate contaminated wastewater through synergistic interactions with its host plants during phytoremediation.

The combination of endophytes and plants for phytoremediation has been reported to be more efficient when compared with endophytes alone (AI-Jawhari 2022). Phytoaugmentation is a variation of phytoremediation that uses plants to stabilize or immobilize contaminants in soil, sediments, or water. Plants are chosen for their ability to tolerate or accumulate pollutants, and their root systems help bind or immobilize contaminants, preventing their movement into the surrounding environment. Phytoaugmentation is an emerging technology that has shown great potential in the remediation of wastewater contaminated with pollutants. This innovative approach harnesses the power of plants and explores their potential applications in treating both domestic and industrial wastewater (Kumar et al. 2021). The inherent ability of plants to uptake and transform specific contaminants can be boosted by incorporating endophytes into the phytoaugmentation process. Endophytic phytoaugmentation involves the introduction of external strains of endophytic bacteria to phytoremediation plants. This process stimulates and enhances the interactions between plants and microbes, improving efficiency in remediation efforts (Redfern and Gunsch 2016). The interaction of plants with associated endophytes for bioremediation of environmental contaminants is a promising technology as the process enhances the degradation capacity of the endophytes (Stępniewska and Kuźniar 2013).

The application of aquatic plants in association with endophytes in the remediation of aquatic systems not only rids the surface water of contaminants but also protects the groundwater from contamination. Decontamination of soils via phytoremediation is a sustainable means of protecting the groundwater. There is no doubt that endophytes are a remarkable collection of microorganisms with the ability to tolerate and eradicate pollutants in aquatic environments in a sustainable manner. Endophytes have an excellent tolerance and eradication potential and could be sampled from various hosts. To benefit their operations, improvements and innovations are also possible for endophytes; this entails researching and comprehending the precise mechanisms that endophytes use for bioremediation. Using updated technology, it is imperative to highlight endophytes' roles in effective environmental remediation and bioresource conservation. This will benefit people and the environment and contribute to preserving the natural world.

5.6 Disinfection of Water for Irrigation Systems

The teeming population of the globe demands abundant food and guaranteed security; however, the effects of global climate change are impeding the production of food crops and other agricultural produce (Bortolini et al. 2018). The agricultural sector is the largest consumer of water, and based on the published report on the FAO-AQUASTAT database (2022), agricultural water withdrawal is the amount of self-supplied water available for irrigation, livestock management and aquacultural practice. The irrigation water withdrawal is the amount of water withdrawn for irrigation purposes, while the irrigation water requirement is the amount needed for optimal crop production. It consists of water (exclusive of precipitation and soil moisture) to meet absolute crop water requirements. It may be expressed in water depth (km^3/year) or water volume (109 m^3/year).

There is an increasing awareness of the efficient use of water resources. One of the ways encouraged to relieve difficulties in water access and ensure water availability for agriculture is by taking full advantage of low-quality water for irrigation needs, such as brackish, high-sand and surface-lake waters as well as reclaimed municipal wastewater, rather than pumping out groundwater from deeper water table (Zhou et al. 2019). The irrigation water quality can be assessed based on its agronomic impact, sanitary risk on public health, ease of field distribution, or management of the water circulation system (Toze 2006). Irrigation water is preponderantly sourced from rivers and dams and conveyed through open channels into the farm water storage before distribution to the crop field (Koech and Langat 2018). Though irrigation water sources with compromised hygiene often do not affect crop yield, but may impose danger on public health due to pathogens transmission, most notably when fresh vegetables are involved (Bortolini et al. 2018).

Low-quality water used for irrigation would unarguably diminish the quality of the soil, increasing amounts of heavy metals in the soil and food crops, encouraging high-level organic contaminants, and thus negates the campaign for food quality and safety toward sustainable development goal (Hass et al. 2010; Allende and Monaghan 2015). Additionally, increasing evidence suggests the occurrence of geogenic contaminants in open water sources. The appearance of trace elements and the increasing use of wastewater have highlighted the vulnerability and complexities of the composition of irrigation water and its long-term effect on food quality and public health. (Malakar et al. 2019) Hence, the rapidly changing quality of irrigation water urgently needs closer attention to understand and predict long-term effects on soils and food crops.

For instance, arsenic, which is notorious for its carcinogenic trait and as a poisonous heavy metal, is widely distributed in natural aquatic environments, constituting an enormous threat to public health (Nordstrom 2002). The plants can easily pick up such geogenic contaminants, among others, through transpiration pull across the irrigation water pathway, and then bio-amplified in the human tissue through consumption of affected crops, where it would wreak havoc on the human metabolic system. Interestingly, recent research dynamics are moving toward adopting a biocontrol approach in cleaning contaminated environments because it guarantees sustainability and cost-effectiveness (Plewniak et al. 2018). Microbial oxidation of arsenic (III) ions is one of the most promising approaches as a precursor step in removing the arsenic ions from contaminated groundwater (Crognale et al. 2019).

The biological cleanup of water resources is dependent absolutely on the application of bacteria strains with no trace of virulent determinants, acting as biocatalysts for biochemical oxidation, degradation of pollutants in the aquatic medium and establishment of the biologically stable water environment to prevent the growth of microorganisms in the water distribution system (Abu Hasan et al. 2020). Most bacterial endophytes are neither phytopathogens nor human pathogens. They invade and live mutually within the tissue of the host plants. Apart from the endophytes enjoying protective shelter from the host, they also benefit from organic nutrients and guaranteed support for life cycle transmission from one generation to the next. In contrast, the host plants become more viable and resistant to stress, herbivores, pests, and pathogens (Mengistu 2020).

Although, only a few studies have been reported on the direct application of endophytes in surface or wastewater treatments. When we consider the effectiveness and inevitable contribution of endophytes in their ecological niche, endophytes may present a reservoir of viable and eco-friendly biological agents for the cleanup of water resources intended for irrigation. More importantly, considering their readily established mutual association with plants, residual endophyte cells pose no threat to the crops or the environment even after the cleanup or treatment of irrigation water. Rather, they confer more crop protection and growth support as a secondary effect.

5.7 Conclusion

Agricultural practice accounts for the highest annual water demand; a substantial amount goes into absolute crop water requirements. The reuse of municipal wastewater is fast becoming an alternative irrigation water source, besides external surface water sources, due to unprecedented water shortage in most of the world driven by the conspicuous changes in the global climatic condition. Unarguably, these water sources are heavily polluted by default, requiring adequate and effective cleanup to avoid the unintending upset of significant biodiversity, carryover effects on public health and gross reduction in food quality. Several studies have established the efficiency of microorganisms, bacteria and fungi in treating wastewater for bioremediation and biotransformation. Endophytes have become handy in this regard, and their potential has not been fully exploited. More attention is required to be paid to this valuable group of microorganisms. Their application in decontaminating and bio-cleaning waste and surface water for irrigation purposes promises to be efficient, eco-friendly and sustainable. It is a cost-effective approach that can be achieved with cheap technology to support global sustainable food security and safety goals.

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