Symbiosis (2024) 92:323–354
https://doi.org/10.1007/s13199-024-00981-9

Exploring macrophytes' microbial populations dynamics to enhance bioremediation in constructed wetlands for industrial pollutants removal in sustainable wastewater treatment

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Received: 28 July 2023 / Accepted: 15 February 2024 / Published online: 15 March 2024

Abstract

Toxic contaminants from intense industrial operations are entering wetlands, harming human health and biodiversity. Macrophytes serve as principal producers in aquatic environments including natural wetlands, providing shelter, food, and, most crucially, intricate relationships with the surrounding microbial assemblage for support and microorganisms attachment. Wetlands have been nature's kidneys, for filtering water. Recent research has examined macrophytes' phytoremediation abilities. With recent improvements focused on engineered wetland technology, microbiological characterization, and genetic engineering, phytoremediation strategies have also benefited. However, little research has examined the role surrounding microbial population play on macrophyte efficiency in pollutant degradation, the extent and even mechanisms of these interactions, and their potential utility in wastewater treatment of diverse industrial effluents. Our bid for greener solutions implies that macrophyte-microorganisms' interspecific interactions for in situ treatment of effluents should be optimised to remove contaminants before discharge in natural waterbodies or for recycle water usage. This review provides for the varied types of plants and microbial interspecific interactions beneficial to effective phytoremediation processes in artificial wetland design as well as considerations and modifications in constructed wetland designs necessary to improve the bioremediation processes. Additionally, the review discusses the latest advancements in genetic engineering techniques that can enhance the effectiveness of phyto-assisted wastewater treatment. We will also explore the potential utilisation of invasive species for their demonstrated ability to remove pollutants in the controlled setting of constructed wetlands.

Keywords Effluents · Water-treatments · Wastewater · Bioremediation · Bio-mitigation

1 Introduction

As we face the challenges of environmental pollution, there is a need to develop sustainable remediation approaches and effective strategies for the treatment of industrial effluents brought about by economic developments. Constructed wetlands have emerged as favorable option for bioremediation due to their ecological significance, one major support framework present in all wetlands are the plants (macrophytes) enabled by the interplay of endophytic and rhizospheric dwelling microorganisms that participate in the degradation of compounds including pollutants within the area covered by these plants (Supreeth 2022; Borgulat et al. 2022). Aquatic plants (macrophytes) provide a structure that enhances flocculation and sedimentation, and the conditions for microbial activities to stabilize and degrade pollutants (Kochi et al. 2020). This is possible because the stems, leaves, and roots provide surfaces for microbial adhesion between the soil/silt interphase and the water column (tidal currents). These surfaces provide protection and an environment for the development of microbial communities (Srivastava et al. 2017; Onaebi et al. 2020).

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Although found abundantly in aquatic environments, free-living microorganisms are less efficient at sourcing and processing nutrients, than consortia dwelling microorganisms, especially those that live in close proximity to these aquatic plants. This is because concerted enzymes from consortium cooperation are necessary to degrade complex substrates, as such, it is beneficial to reside within groups. Additionally, the type and composition of nutrients present modifies microbial species composition and changes ecological communities as they attempt to adapt to these chemical compounds, which in turn affects ecological system performance. Other environmental pressures that affect microbial fluxes also change microbial communities. Microorganisms need carbon to proliferate and increase enzyme levels (metabolic activities) in any given environment (Gupta et al. 2017; Huang et al. 2020). Studies in bioprospecting have shown that the assimilation of carbon and other essential nutrients necessary for metabolic activities and biomass growth induces cooperation amongst microorganisms, inadvertently leading to the production of important biological products used in industries such as food, medicine, agriculture, water, and energy recovery (Abbas et al. 2021).

Pertinently, these macrophyte-microbe interactions can be found in root organic deposits, in stems and leaves (endophytic), enhanced by varied nutrient contents and the type of fortuitous stem/root-associated microbial communities (Shaikh et al. 2018). The rhizosphere is a narrow zone of soil surrounding aquatic plant roots where root exudates cause biological activity (Clairmont et al. 2019). The rhizosphere attracts bacteria and other microorganisms that feed on decaying root material from sloughed off border cells and mucilage (thick, viscous, high molecular weight, insoluble, polysaccharide-rich material that lubricates roots against desiccation) (Zhalnina et al. 2018). Rhizo-deposition enables microorganisms to grow on roots (Yadav et al. 2015). Root exudates contain sugars, nucleotides, amino acids, organic acids, phenolic compounds, enzymes, phytohormones, and vitamins that can attract or inhibit microorganisms, act as signal molecules in the rhizosphere, and sequester hazardous toxic elements (e.g. cadmium, chromium VI, and others). Chemical components of root exudates may facilitate symbiotic or mutualistic associations, such as N_2 fixation and mycorrhizal associations, or deter microorganisms via negative associations, such as competition, pathogenesis, and parasitism among plants (Pathan et al. 2020). Rhizosphere sediment, plants, and microorganisms regulate microbial diversity and dynamics (Olanrewaju et al. 2019). In addition, compounds that are absorbed by the plants, interact with endophytic micoroganisms found within the stem as well as the leaves.

Apart from the macrophyte selection and enhancement of microbial diversity, the removal of industrial pollutants in constructed wetlands involves a combination of physical, chemical, and biological processes. This involves incorporating other strategies such as the constructed wetland design to allow for sufficient contact time between the pollutants and biota and promoting effective biological and chemical processes for the removal of pollutants (Hassan et al. 2021). Considering sedimentation traps and filtrations strips will ensure a consistent flow velocity within the constructed wetland to enable sedimentation of unwanted particles and pollutants and allowing the capture and filtration runoffs to prevent transport of the pollutants further in the wetlands (Mangangka 2013). These strategies, when integrated together will contribute to the effectiveness of constructed wetlands in removing industrial pollutants.

As we progressively look for sustainable approaches to wastewater treatment, our understanding of the phytodegradation process and the application to phyto-assisted bioremediation must integrate optimization processes to improve the removal of pollutants from contaminated water, with emphasis and consideration placed on ensuring specialized treatments for various industrial wastewaters. Thus, this review intends to present various approaches to consider in integrating phytoremediation within an artificial wetland construction that considers the importance of macrophyte-microorganisms' interactions in pollutants removal. Further, the review will highlight the broader implications of this approach for environmental management and pioneering the development of innovative and eco-friendly strategies to reduce the challenges posed by industrial pollution.

2 The macrophyte as a micro-ecological system

The rhizosphere food web can be divided into three distinct channels, each with its own energy source: detritus-dependent fungi and bacterial species, and root energy-dependent invertebrates, symbiotic species, and some arthropods. Because the amount of detritus available and the role of root sloughing change as roots grow and age, the food web is constantly in a state of flux. This bacterial channel is considered a faster channel because species can focus on more accessible resources in the rhizosphere and have a faster reproduction rate than fungal channels. The size and distribution of microbial assemblages in this zone are directly related to the system's nutrient resources' quality and quantity. Due to the introduction of exudates and the relationships that they maintain, aquatic plants have an impact on which microbial species in the rhizosphere are selected against. The amount of root exudates that plants can produce has an impact on the rhizosphere's microbial communities (Zhu and Sikora 1995). Cell counts in the root zone are several orders of magnitude higher than in plant-free soil. The microbial community in rhizosphere roots is more diverse, active, and synergistic implying that microbial genes outnumber plant genes in the rhizosphere (Mendes et al. 2013). Most microbial communities adapt quickly to natural perturbations or external nutrition loading (Reddy et al. 2002). This rhizosphere connection is found in semi-arid soils and wetland habitats (Aguirre-Garrido et al. 2012; Hong et al. 2015).

The occurrence of sedimentation stores inorganic and organic nutrients before releasing them back into the water column. Microbial communities in sediments are critical to wetland functions because they play important roles in substance export, regeneration, and biogeochemical cycling (carbon, nitrogen, sulphur, and iron) (Cheung et al. 2018). Plants can grow in water-saturated sediments, making wetlands ecosystems unique. This allows plants to have adventitious roots/rhizomes with aerenchymatous tissues, which improves oxygen transfer via air pressure gradients and passive mechanisms such as diffusion, and creates an oxygenated aqueous layer around root hairs (Allen 1997). Wetlands' perennial or periodic flooding and plant roots create a dual oxic and anoxic environment that encourages aerobic and anaerobic microbial assemblages (De Mandal et al. 2020). Aerobic bacteria thrive in an oxygen-rich environment provided by roots.

An oxygen-deficient environment promotes anaerobic microbes farthest from the roots (Sand-Jensen et al. 1982). Microorganisms in the anoxic hydric zone produce an oxic surface layer, and redox stratification occurs in the oxygen-deficient zone (De Mandal et al. 2020). Oxygen levels at root respiration sites are regulated by open lacunars in stems, roots, and rhizomes. This gaseous space serves as an oxygen conduit from photosynthetic shoot tissue to subsurface tissue, where aerobic processes keep roots absorptive for nutrient uptake (Bedford et al. 1991). The space between the root hairs is populated by anaerobic microorganisms (which grow at a slower rate). The plant rhizosphere is home to significant quantities of culturable microbes that can benefit humanity due to the presence of aerobes and anaerobes that promote fast cycling (rapid use of carbon sources) (Ghermandi et al. 2010). Individual microbes can benefit plants, but when two or more interact, additive and synergistic effects are expected.

Multiple species can play various roles in a rhizosphere ecosystem. Many rhizosphere microorganisms, for example, provide transformed compounds like nitrates for plant absorption and assimilation, which aids crop production (N_2 fixation) by increasing soil/silt fertility. Others offer defence against infections and illnesses. The microbes at this site tend to produce pharmaceutical-grade antibodies. Because of root exudates and metabolic products of symbiotic and pathogenic bacteria, much of the nutrient cycling and disease suppression by plant antibodies occurs near the roots. Due to rhizosphere effects, enriched microorganisms near plant roots improve biodegradation of harmful contaminants (Xiong et al. 2021). These contaminants in the root zone are biodegraded by rhizospheric inhabitants. Plants boost bioremediation by increasing microbial populations and soil metabolism. In wetlands, plant microbiota improves plant uptake of mineral and organic substances from substrates, similar to the role played by land plant microbiome (Alegria-Terrazas et al. 2016). Biodegradable peroxidases and laccases are secreted by root tissues and bacteria. Microbial enzymes and biodegradation are activated by root exudates. The presence of oxygen in the rhizosphere promotes oxidative biodegradation by oxygenases. Plants are super-organisms that rely on their microbiome for specialised functions and characteristics. Macrophytes can influence sediment pollutant removal efficiency due to differences in plant and sediment composition and favourable radial oxygen loss (ROL).

It has been observed that *Arabidopsis* and agricultural crops influence and benefit from the connected rhizosphere microbial community in the terrestrial landscape (Pérez-Jaramillo et al. 2018; Schmidt et al. 2019). Freshwater hydrophyte rhizospheres also have these metabolic interactions. Most studies focus on specific functional groups, such as ammonia-oxidisers (Huang et al. 2016), dentrifiers (Yin et al. 2020), and anammox bacteria (Zhang et al. 2021). In the past, Collins, and colleagues (2004) demonstrated that, while microbes can grow on any surface, the presence of plants affects microbial composition and abundance. Other studies have shown that plant species influence microbial frequency (Qin et al. 2017; Pietrangelo et al. 2018; Fang et al. 2021). This suggests that specific interactions between plants and their host microorganisms have helped them adapt to new environments and dominate various ecosystems. Vymazal (2007) discovered significant differences in microbial diversity in *Phragmitis australis* and *Phalaris arundinacea* rhizospheres. Similarly, Kyambadde et al. (2004) proposed that plant morphology influences microbial frequency, citing the instance of *Cyperus papyrus* which has a larger root surface and microbial density than *Miscanthidium violacuum*.

Wetland microbial organisation differs from terrestrial microbial organisation due to oxygen diffusion and soil physicochemical changes (De Mandal et al. 2020). Microbial communities increase biomass and enzyme activity in response to nutrient fluxes, influencing biogeochemical processes and nutrient cycles such as carbon, sulphur, nitrogen, and lead, which affect water quality and productivity (Cheung et al. 2018). It is undeniable that anthropogenic activities have permanently altered the hydrosphere, posing a threat to these microbial communities. Lamers et al. (2012) investigated the impact of microbial communities on aquatic plant growth and performance. The findings show that microbe-catalyzed biogeochemical conversions regulate the composition and distribution of wetland vegetation.

The nitrogen, sulphur, and iron cycles are among the most notable conversions.

Amongst the various types of macrophytes, emergent macrophytes are the most productive because they can absorb resources from the hydrosphere, and atmosphere (Westlake 1965) as shown in Fig. 1. Their stems and leaves extend above the water's surface enabling carbon fixation and photosynthesis. Macrophytes, unlike terrestrial plants, anchor in submerged, anoxic sediments. Macrophytes provide an additional oxygen source for microorganisms in the rhizoplane (area directly in contact with the root surface) and the rhizosphere (sediment area loosely attached but influenced by the root), promoting aerobic micro-niches in an otherwise anaerobic environment, such as wetland sediment. Interestingly, the sulphate-rich silt found in wetlands, provides anaerobic microorganisms with an enabling environment. These group of microorganisms are very important in elements (including pollutants) removal from the environment. They use varied strategies such as bioabsorption, bioadsorption, bioaccumulation, and biodegradation. These processes are integrated into the cellular machinery and/or biochemical pathways of these microorganisms (Goud et al. 2020).

Furthermore, strong, fibrous stems improve tissue present in macrophytes, which aids in aeration. For example, macrophytes such as *Zizania latifolio* and *Phragmites australis* have this structure, allowing them to translocate oxygen and other primary, secondary, and bioactive compounds into the rhizosphere for plant growth (Toyama et al. 2011), thereby establishing an oxygen-rich sediment microenvironment. By regulating N and P fluxes, emerging macrophytes can help to prevent eutrophication of the mainland and coastal regions. Wetland nitrification and denitrification may account for up to 80% of total N removal (Jahangir et al. 2016). Nitrification (the oxidation of ammonia to nitrate) is primarily an aerobic autotrophic process, whereas denitrification (the step-wise conversion of nitrate to nitrogen gas) is primarily an anaerobic process. At the root surface of emergent macrophytes, two opposing conditions for nitrification and denitrification can co-occur, with radical oxygen loss (ROL) providing oxic microniches for nitrification in an anaerobic environment.

3 Macrophytes involvement in interspecific interactions within wetlands

De Mandal et al. (2020), espouse that despite the great strides made in studying the functional and structural components and dynamics of microbial communities in natural wetlands, further research is needed to unravel the microbial "dark matter" and metabolic potential and their functional properties in these rare ecosystems. Compared to terrestrial

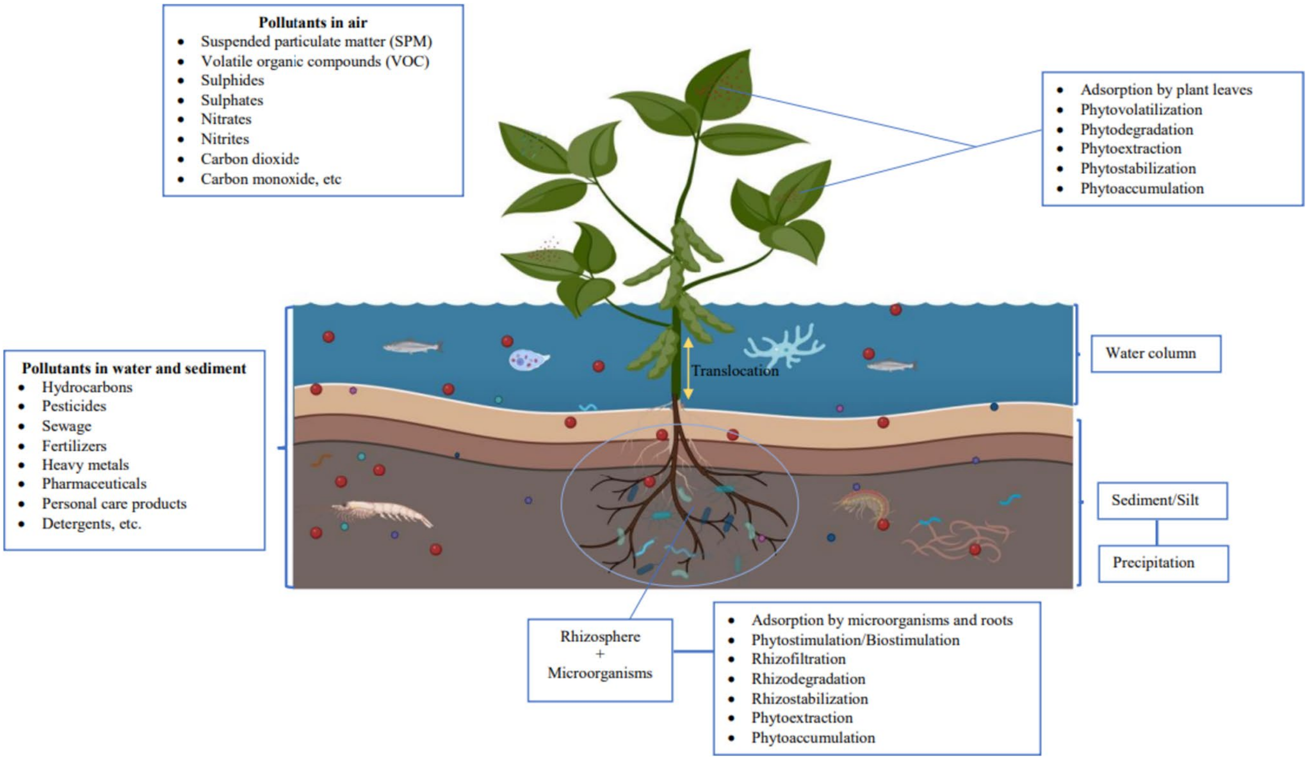


Fig. 1 Microbe-plant interactions in pollutant degradation in (1). Water, (2). Soil and (3). Air

and aquatic ecosystems, wetland microbial assemblages are understudied. Thus, a more comprehensive understanding of microbial structures and ecological principles governing community organisation is needed. Additionally, Cheung et al. (2018) states that elucidating the complex community structure and kinetics is essential to understanding the microbial diversity that governs wetlands, considering it is a reservoir of untapped secondary bioactive compounds that can be used for bioremediation of pernicious compounds that threaten the ecosystem.

To this end, microbial network analysis conducted by various researchers over the years have helped our understanding by revealing the complex microbial biomes and the functional roles of the various inhabitants of these unique environmental niches. Current wetland co-occurrence networks tend to focus on bacterial and fungal assemblages in salt marshes (Du et al. 2020; Gao et al. 2021; Wang et al. 2023; Zhang et al. 2023). Table 1 shows some of the interspecific relationships within macrophytes' rhozosphere that have been identified in wetland and aquatic environments.

4 The importance of phyto-assisted degradation of organic pollutants

Organic molecules released into the environment as a result of numerous human actions pose a serious threat to the ecosystem due to their toxicity, hydrophobicity, and resistance to degradation. Organic chemicals like hydrocarbons, polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls, chlorophenols, toluene, benzene, phenols, trinitrotoluene, herbicides, and pesticides impede soil-associated microbial development and metabolic processes even at low concentrations (Sun et al. 2013). These dangerous chemicals are made up of organic chemical compounds (carbon bases) and mixtures that are primarily products or byproducts of industrial operations, chemical manufacturing, and wastes that are resistant to external degradation via biological methods. Humans are extremely vulnerable to these pollutants (Karaś et al. 2021). The pollution of aquatic environments by organic compounds is regarded as a critical issue because it affects biodiversity, depletes aquatic systems and devastates the environment. Furthermore, due to their toxicity, they can enter the food chain and cause genotoxicity and carcinogenic effects in both animals and humans (Nanseu-Njiki et al. 2010).

Conventional physiochemical approaches to cleaning up organic contaminants from water can be difficult, expensive, and environmentally damaging (Marques et al. 2011). Phytoremediation, or the use of plants to decontaminate polluted water, has gained popularity and is regarded as an effective, inexpensive, and environmentally friendly technique. Nonetheless, plants suited for phytoremediation must become acclimated to contaminated surroundings. However, the existence of organic contaminants tends to inhibit plant growth and, ultimately, the performance of phytoremediation (Thion et al. 2013). The implication is that optimisation and strategies need to be employed for effective bioremediation to be achieved using plants. Recent advances in environmental protection have shown that a combination system of microbes and plants can effectively clean up pollutants. When appropriate plants and microorganisms are introduced into a nutritionally deficient but contaminant-rich ecosystem (as shown in Fig. 1), the plants interact through the rhizosphere and the roots, the microorganisms form a symbiotic relationship necessary for survival in such adverse conditions. Plants emit compounds that invite microbes to interact. This association causes increased germination and root elongation, resulting in increased pollutant degradation in both the rhizosphere and the phyllosphere (Supreeth 2022). Plant-associated bacteria can alter these compounds through metabolic and enzymatic processes, enhancing the efficacy of phytoremediation (Zhu et al. 2016). Plant-associated bacteria include endophytic, phyllospheric, and rhizospheric bacteria. Although, endophytic bacteria appear to be the best option for improving phytoremediation (Karaś et al. 2021). This is due to their ability to stimulate growth, activate defence system, and boost plant tolerance to organic pollutants (Ma et al. 2015).

5 Endophytes assisted phytoremediation of hydrocarbons

Many endophytic bacteria not only aid in plant development but also improve the elimination of organic contaminants, lowering plant toxicity. Horizontal genes transfer (HGT) has been determined to be the primary mechanism by which bacteria acquire novel capabilities, allowing them to respond quickly to environmental changes (Wang et al. 2010). Once the native population of endophytes acquire these new genes, they are able to tolerate and even proliferate with the new ability to degrade these organic pollutants (Afzal et al. 2014). Moreover, HGT enables the formation of endophytes with heterologous gene expression and novel catabolic pathways, particularly with interconnected species donors and recipients (Hardoim et al. 2008). Azadi and Shojaei (2020) discovered that *Pseudomonas* sp. has genes that enable it to degrade nearly all PAHs with fewer than four aromatic rings. Zhu and colleagues (2016) used two endophytes (*Pseudomonas* sp. P-3 and *Stenotrophomonas* sp. P-1) to degrade PAHs into simpler molecules.

Previously, *Burkholderia phytofirmans* PSJN, was discovered as an endophytic bacterial strain that colonises a wide range of plants, enhancing their growth. The genome

Table 1 Macrophytes' rhizosphere interspecific interactions with various organisms in wetlands

Interaction	Function in ecosystem	Examples	References
Archaea	• Methanogenesis • Nitrogen cycling as nitrogen fixers, denitrifiers and ammonia-oxidizers • Bio-indicators of global methane emissions • Extreme thermotolerance in halophilic members promotes the production of useful enzymes for biotechnological applications such as esterase, inulinase, cellulose and gelatinase	*Methanospirillum, Thaumarchaeota, Bathyarchaeota, Halofurax* *Halococcus, Nitrososphaera, Nitrosotalea, Nitrosopumilus, Euryarchaeota, Crenarchaeota, Wasearchaeota*	Krzmarzick et al. 2018; Chen et al. 2019a, b; De Mandal et al. 2020
Bacteria	• Assists macrophytes in the assimilation of dissolved substrates during growth and development • Promotes the degradation of pollutants by macrophytes • Provides protection against antagonistic microorganisms • Controls the production of secondary metabolites • Aerobic and lithoautotrophic bacteria are involved nitrification through the production ammonia monooxygenase (AMO) • Heterotrophic bacteria (anaerobes) are involved in denitrification • Nitrogen fixation through symbiotic relationships in the rhizosphere • Saprophytic bacteria perform various complex compounds transformation to clean up dead decaying root parts • Modulation of biogeochemical cycles and influencing plant growth • Bacteria endophytes create functional biomolecules and participate in pollution degradation through co-metabolism, extraction, and hyper-accumulation processes • Bacteria endophytes promote phytoremediation by increasing nutrient availability, regulating plant development, alleviating toxic stressors, and communicating with microbial populations	*Azotobacter, Klebsiella, Streptomyces, Bacillus megaterium, Pseudomonas*, *Sulfurimonas, Rhenheirmera, Coprothermobacter, Chloroflexi, Acidobacteria*	An et al. 2019; Szabó-Tugyi and Tóth. 2020; Seward et al. 2020; De Mandal et al. 2020; Kumari et al. 2021

Table 1 (continued)

Interaction	Function in ecosystem	Examples	References
Fungi	• They form mutualistic and antagonistic relationships with macrophytes • Arbuscular mycorrhizal fungi from mutualistic relationships linked to vascular bundle systems of herbaceous and woody plants aiding in water and nutrient distribution • Saprophytic fungi are significantly involved in the degradation of cellulose and lignin, simpler compounds which are then used by other microorganisms • Antagonistic fungi prevent root growth and seedling germination and can kill off plants • Fungal pathogens can assist in maintaining plant populations by influencing plant composition and reproductive fitness • Fungal endophytes form symbiotic relationships with host plant helping the plants to adapt to changing conditions in the environment. They also function in defence and enhancement of stress tolerance as well as in latent pathogenicity that assist plants in systematic resistance • Fungal endophytes produce a diverse range of secondary metabolites useful in agriculture, industry, and medicine	*Fusarium, Tricholoma, Mortierella, Trichoderma Penicillium, Entoloma, Tolypocladium, Paecilomyces, Alternaria, Selerophoma, Cladosporium, Cryptococcus, Saccharomyces*	Neori and Agami 2017; Alabid et al. 2018; Freed et al. 2019; Illescas et al. 2020; Gupta et al. 2020; Xie et al. 2020; Barrio-Puque et al. 2020; Park et al. 2021, Fu et al. 2023
Protozoa	• They maintain equilibrium in aquatic microbial food webs • They mediate energy transfer to higher trophic levels in aquatic ecosystems that affects physicochemical properties and biochemical processes of rhizosphere soil • Protozoal grazing in the rhizosphere suppresses plant diseases as they consume plant pathogens • The presence and type of protozoa in water can be used as a bio-indicator of the water quality	*Giardia, Entamoeba histolytica, Cryptosporidium parvum, Testate amoebae, Entamoeba dispar, Entamoeba coli, Endolimax nana, Iodamoeba bütschlii, Euglena acus, Cucurbitella mespiliformis, Codonella acutula Hemiophrys punctata*	Shi et al. 2016; Hou et al. 2016; Joergensen and Wichern 2018; Da Silva et al 2018

of this bacterium is made up of two chromosomes and one plasmid, which contain genes that encode breakdown processes for a wide range of complex organic substances. This bacterium contains genes that code for aliphatic chemical degrading enzymes such as alkane monooxygenase (alkB) and cytochrome P450 hydroxylase. *B. phytofirmans* PSJN's genome also contains 15 genes that encode for dioxygenases enzymes. These enzymes are involved in the aromatic ring fission process. Furthermore, this strain's genome contains an astonishing number of GST genes (24 copies). These genes are components of the operons responsible for the breakdown of aromatic chemicals (Mitter et al. 2013). Similarly, *Burkholderia cepacia* FX2 is a toluene-degrading endophyte that carries a plasmid containing a gene encoding catechol 2,3-dioxygenase, an enzyme important in the degradation of monocyclic aromatic hydrocarbons (Wang et al. 2010).

Endophytic fungi can also be used to manage organic pollutants in the environment. There has been some significant research on the elimination of specific homologous groupings or chemical types in this field (Garnica-Vergara et al. 2016). Endophytic fungi can improve host health and competitiveness by increasing germination and growth rates and improving nutritional element absorption (Aly et al. 2011). In comparison to endophytic bacteria, fungi endophytes are incapable of being primary organic contaminant degraders (Etesami 2018). For example, endophytic *Phomopsis liquidambari* cannot survive on phenolic 4- hydroxybenzoic acid as its sole source of carbon and energy, but it can efficiently degrade polycyclic aromatic hydrocarbons. This endophytic fungus can also degrade N-heterocyclic chemicals such as indole (Chen et al. 2013). Table 2 shows some endophyte assisted phytoremediation of organic pollutants.

6 Rhizobacteria assisted phytoremediation of hydrocarbons

Rhizoremediation has gained acceptance among scientists because plant roots provide a rich environment for bacteria to thrive at the expense of root exudates; bacteria then act as biocatalysts, removing contaminants, particularly around surrounding sediments (Correa-Garcia et al. 2018). Pollutant-degrading rhizobacteria are regarded as plant-growth promoting rhizobacteria (PGPR), in their absence such pollutants would have inhibited plant development. The removal of these inhibitory compounds would help the plant grow (Kanaly and Harayama 2010). Several effective methods for increasing bacterial breakdown efficiency and resistance to pollutants have been developed. PGPR has been demonstrated to increase organic pollutants removal leading to plant germination improvement and survival in severely polluted areas and accelerating root growth and root biomass accumulation (Huang et al. 2004).

Although, ethylene is required for plant growth, but excessive ethylene caused by stress may inhibit growth (Deikman 1997). Remarkably, PGPR stimulate plant development by consuming amino-cyclopropane carboxylic acid (ACC), an immediate precursor to ethylene, and producing 1-aminocyclopropane-1-carboxylate (ACC) deaminase to reduce ethylene secretions in stressed plant (Safronova et al. 2006). Table 3 provides examples of PGPR that have demonstrated abilities to assist and promote organic pollutant degradation.

7 The importance of phyto-assisted degradation of inorganic pollutants

The most prevalent types of pollutants in wetlands are inorganic (toxic elements). These various inorganic contaminants can persist in nature for longer periods of time and travel over long distances with more effectiveness particularly in aquatic environments. Industries have routinely used several aquatic ecological systems as a discharge point for their wastes. Agricultural and domestic pollution are also significant contributors to the production of inorganic contaminants. These toxic elements pollute both surface and groundwater. Inorganic contaminants can accumulate to lethal levels for humans and biological ecological systems. Toxic elements such as chromium, arsenic, zinc, mercury, lead, and nickel are extremely hazardous to humans, plants, and animals, as well as soil fertility. According to Akram et al. (2018), these toxic elements are common in wetlands and their concentrations are quite high due to bioaccumulation. These metal contaminants concentrations tend to rise in living systems because their retention rates are higher than their discharge rates.

Many inorganic pollutants exist in smaller quantities than other pollutants but garner a lot of attention due to their extremely harmful nature. Such trace element emissions pose serious health risks to humans, and these pollutants enter our bodies via the food chain. Inorganic contaminants continue to pique the interest of environmental chemists. They are typically found in minute concentrations in natural waterways, but some are extremely dangerous even at very low concentrations (Hamelink et al. 1994). Metals such as arsenic (As), lead (Pb), cadmium (Cd), nickel (Ni), mercury (Hg), chromium (Cr), cobalt (Co), zinc (Zn), and selenium (Se) are extremely toxic even in trace amounts. Carcinogens will usually contain some forms of toxic elements and dyes; endocrine disruptors containing these varied inorganic elements in different concentrations can also be found hormones, medications, cosmetics, and personal care products. They are discharged either in active forms or as wastes into

Table 2 Endophytes with abilities of phytoremediation promotion and pollutant biodegradation

Endophytes	Host plant(s)	Beneficial Functions	Pollutant(s)	References
Achromobacter	*Arabidopsis thaliana, Chrysopogon* sp.	Biodegradation	Phenolic and BTEX pollutants	Aravind et al. 2010
Actinobacteria sp. *Gammaproteobacteria* sp. *Microbacterium foliorum, Plantibacter flavus*	*Achillea millefolium, Solidago canadensis, Trifolium aureum, Dactyls glomerata*	Biodegradation	Hydrocarbons	Ambrose et al. 2015
Azospirillum sp. and *Pseudomonas stutzeri*	*Dactylis glomerata*	Biodegradation	Anthracene, phenanthrene, and pyrene and diesel fuel	Grishchenkov et al. 2003
Rhizobium sp. *Pseudomonas* sp. *Stenotrophomonas* sp. *Rhodococcus* sp.	*Lotus corniculatus, Oenothera biennis*	Plant growth regulation	Hydrocarbons	Ashraf et al. 2018
Pseudomonas sp. Microbacterium sp. and *Rhodococcus sp.*	*Lolium perenne*	Biodegradation, Plant growth regulation	Petroleum hydrocarbons	Ijaz et al. 2016
Pseudomonas putida PD1	*Salix discolor* S-365, *Salix purpurea* 94006	Biodegradation, Plant growth regulation	Polyaromatic hydrocarbons	Wang et al. 2017a, b
Phomopsis liquidambari	*Oryza sativa L. Arachis hypogaea L*	Biodegradation, Plant growth regulation, Nutrient supply	Phenanthrene, phenolic acids	Wang et al. 2017a, b
Pestalotiopsis sp.	*Nepenthes ampullaria*	Biodegradation, Co-metabolism	Polyurethane by-products	Wang et al. 2015
A mixture of selected endophytic bacteria	*Juncus acutus*	Biodegradation, Plant growth regulation, Stresses alleviation	Bisphenol A, ciprofloxacin, sulfamethoxazole	Zahoor et al. 2017
Lewia sp. *Mesorhizobium* sp. HN3	*Festuca arundinacea*	Stresses alleviation, Plant growth regulation	Hydrocarbon mixture Chlorpyrifos (Pesticide)	Bisht et al. 2015
Consortia of bacteria	*Lupinus luteus*	Biodegradation	Organic pollutants	Leroy et al. 2017
Burkholderia fungorum DBT1	*Populus deltoids, Populus nigra*	Stresses alleviation, Plant growth regulation	Naphthalene, phenanthrene, fluorene, and dibenzothiophene	
Burkholderia cepacia VM1468	*Lupinus luteus*	Stresses alleviation	Trichloroethylene	Lumactud et al. 2016
Bacillus cereus ERBP	*Clitoria ternatea, Zamioculcas zamiifolia*	Biodegradation, Plant growth regulation, Stresses alleviation	Formaldehyde	Fu et al. 2018
Pseudomonas sp. (AIEB-4), *Alcaligenes sp*. (AIEB-6), *Achromobacter sp.* (AIEB-7)	*Cannabis sativa*	Biodegradation	Phenols and Benzene	Iqbal et al. 2018
P. putida VM1450	*Populus deltoids*	Biodegradation	2,4-dichlorophenoxyacetic acid (2,4-D) (Herbicide)	Germaine et al. 2006

Table 3 PGPR with abilities of phytoremediation promotion and organic pollutant biodegradation

PGPR	Host plant(s)	Beneficial features	Pollutant(s)	References
Pseudomonas putida PD1	*Poplus tremula L*	Phytoprotection Phenanthrene degradation	Phenanthrene	Khan et al. 2014
Streptomyces griseorubiginosus strains DS24 and DS4	*Miscanthus giganteus* (roots)	Siderophore, IAA production	Diclofenac and sulfamethoxazole	Sauvêtre et al. 2020
Enterobacter sp. strain PDN3	*Poplar* (hybrid*)*	TCE degradation	Trichloroethylene (TCE)	Kang et al. 2012
Burkholderia cepacia strain FX2	*Zea mays Triticum durum*	Toluene degradation	Toluene	Wang et al. 2010
Staphylococcus sp. BJ106	*Alopecurus aequalis*	Plant growth regulation and enhanced degradation	Pyrene	Sun et al. 2014
Enterobacter sp. PDN3	*Populus deltoides Populus nigra*	TCE degradation	TCE	Kang et al. 2012
Enterobacter ludwigii	*Lolium multiflorum var. Taurus Lotus corniculatus Medicago sativa*	Hydrocarbon degradation and ACC deaminase abilities	Diesel	Yousaf et al. 2011
Pseudomonas sp. 1FWK	*Oenothera biennis*	Plant growth regulation	Diesel	Pawlik et al. 2017
Bacillus sp. SBER3	*Populus deltoides*	Plant growth regulation	Anthracene, naphthalene, benzene, toluene, xylene	Bisht et al. 2014
Bacillus cereus NI	*Dracaena sanderiana Pantoea dispersa*	High TDS tolerance and alkalinity	Bisphenol A	Suyamud et al. 2020
Bacillus mojavensis ATHE13 *Bacillus licheniformis* ATHE9 (F1)	*Festuca arundinacea*	PAH degradation Increased biomass	Naphthalene, Acenaphthene, Acenaphthylene, Phenanthrene, Chrysene, Anthracene, Benzo[a] anthracene, Benzo[a] pyrene, Dibenzo[a,h] anthracene, Benzo[ghi] perylene	Eskandary et al. 2017
Enterobacter sp. PDN3	*Populus deltoides Populus nigra*	Plant growth regulation	Trichloroethylene (TCE)	Doty et al. 2017
Bacillus safensis ZY16	*Chloris vigrata Sw*	Increased plant biomass and plant growth regulation and significant improvement on hydrocarbon degradation	Diesel and PAHs (n-undecane, n-hexadecane, n-octacosane, naphthalene, phenanthrene and pyrene	Wu et al. 2019

aquatic environments. Consequently, the direct discharge of metal-containing effluents into water sources, toxic elements is prevalent in the environment. Humans consume these metals through their food and drinking water. Although, some toxic elements, such as cobalt, copper, iron, manganese, vanadium, and zinc, are essential elements that the body requires in trace amounts for various biochemical systems. Most of these toxic elements have serious health consequences on a wide range of human organs, including eye, nose, skin, and internal organs where they cause headaches, irritations, discomfort, diarrhoea, hematemesis, vomiting, cirrhosis, necrosis, low blood pressure, hypertension, and gastrointestinal distress (Verma et al. 2017).

Arsenic poisoning from contaminated water causes lung, liver, and bladder cancer. Cadmium contamination in water can harm the kidneys and lungs and cause bone fragility. Lead consumption, in particular, has a devastating effect. It has the potential to cause brain and kidney damage. A small amount of lead can disrupt children's learning by causing memory loss, impaired reaction functions, and aggressive behaviour (Sun et al. 2017). Pregnant women may experience miscarriage as a result of increased lead consumption, and it also inhibits sperm production in males. Mercury is also considered a global pollutant because it is widely used for a variety of purposes, and as a result, it has a wide range of negative health effects. Mercury enters the body through blood vessels and exits through urination and scat. It causes a variety of side effects, including loss of peripheral vision, impaired movement coordination, muscle weakness, and speech and hearing impairment (Marques et al. 2011).

However, it is possible to remove these toxic elements from water using a variety of phytoremediation techniques. Aquatic macrophytes like *Hydrilla verticillata* and *Elodea canadensis* have been shown to accumulate large amounts of Cd in their tissues from contaminated sediments (Sood et al. 2011). Although, due to three major constraints: low macrophyte biomass, restricted root development, and limited metal extraction, the effectiveness of phytoremediation is insufficient to be commercially viable (Muehe et al. 2015). Therefore, rhizosphere bacteria, particularly those with metal resistance and plant growth-promoting abilities, have received a lot of attention for their ability to improve the efficacy of phytoremediation (Rezania et al. 2016).

8 Endophytes assisted phytoremediation of toxic elements

Currently, the majority of putative endophytic bacteria with hazardous metal resistance have mostly been identified in plant roots. Endophytes like *Bacillus* sp. *Pseudomonas* sp. and *Achromobacter* sp. can help plants extract mixed heavy metal contaminants, as Babu et al. (2013) demonstrated when they isolated a *Bacillus thuringiensis* strain from the roots of *Pinus sylvestris*. This strain, known as GSB-1, produced phytohormones that stimulate plant growth while also hastening the removal of potentially hazardous metals from mining tailings. For example, chlorophyll content, biomass output, and heavy metal abstraction (e.g. Cu, As, Ni, Zn, and Pb) in plant seedlings increased after GSB-1 co-cultivation. *Arthrobacter* and *Microbacterium* strains colonised the intercellular gaps of root and leaf epidermal tissues extensively, according to Visioli et al. (2015). Furthermore, when compared to other isolates, these endophytes showed excellent plant growth promoting properties. Inoculation using a consortium seemingly improved phytoextraction, translocation, and removal of mixed metals (Fe, Ni, Cu, and Co) from soil. Moreover, endophytic fungi have been extensively studied for their ability to reduce metal toxicity and increase phytoremediation efficiency (Deng and Cao 2017). Some examples of endophytes-assisted phytoremediation for inorganic contaminants is shown in Table 4.

9 Rhizobacteria assisted phytoremediation of toxic elements

The microbial population of the rhizosphere may directly drive root development, promoting plant growth, heavy metal tolerance, and plant fitness (Fasani et al. 2018). Plant growth-promoting rhizobacteria (PGPR) have been discovered to have a high potential for improving the efficacy of phytoremediation. Plant growth and fitness can be enhanced by PGPR, which can also protect plants from infections, increase plant tolerance to toxic elements, improve plant nutrient and heavy metal absorption, as well as aid in translocation. This is accomplished through the production of various chemicals, such as organic acids, siderophores, antibiotics, enzymes, and phytohormones (Ma et al. 2011).

PGPR can synthesise the enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which degrades the ethylene precursor ACC. PGPR can help plants grow by producing ACC deaminase, which reduces ethylene synthesis (Glick 2014). Plants inoculated with PGPR containing ACC deaminase produced more biomass, as evidenced by increased root, and shoot densities, resulting in greater heavy metal absorption and phytoremediation effectiveness (Arshad et al. 2007). Furthermore, PGPR can produce bacterial auxin, indole-3-acetic acid (IAA) to promote lateral root initiation and root hair production, thereby increasing plant growth and assisting in phytoremediation (DalCorso et al. 2019). Arbuscular mycorrhizal fungus (AMF) is another important microbial community that may aid plants in phytoremediation. AMF in rhizospheres increases water and nutrient absorption as well as heavy metal bioavailability by increasing the absorptive surface area of plant roots via the large hyphal network (Göhre and Paszkowski 2006). Arbuscular mycorrhizal fungi secrete phytohormones that stimulate plant growth and aid in phytoremediation (Vamerali et al. 2010).

The phyto-bacteria system has been shown to be more efficient than its components at removing toxic elements. Many different microbial communities, according to Dell'Amico et al. (2005), can withstand high heavy metal concentrations when living in rhizosphere soils and rhizoplanes. As molecular biology advances, genetically modified rhizobacteria with pollution degradation genes are being developed to carry out rhizospheric bioremediation. Mercury is considered the most dangerous heavy metal in the environment. Mercury biotransformation by bacteria is reliant on the expression of *mer* genes cloned from mercury-resistant bacteria. *Caprivoidis metallidurans* NSR33 is a candidate broad-spectrum mercury resistant recombinant bacterial strain that has been touted for its ability to degrade mercury in wastewater. Researchers were able to create a bacterial strain with two large plasmids (pMOL28 and Pmol30) housed in a meR7ADLF operon using recombinant DNA technology. The plasmids exhibit lower levels of resistance to mercury when isolated; however, when fused together, broad-spectrum mercury resistance is achieved (Rojas et al. 2011). Similarly, recent efforts to eliminate arsenic from the environment have focused on developing genetically modified organisms (GMOs) capable of degrading arsenic at maximum levels in the shortest amount of time. Recent studies show that microbial flora removed 2.2 – 4.5 percent of volatile arsenic after 30 days of treatment; thus, genetic engineering (GE) can be used to improve arsenic volatilization and removal efficiency. Cloning an *arsM* gene isolated from *Sphingomonas desiccabilis* and *Bacillus idriensis* into *Escherichia coli* in

Table 4 Endophytes with abilities of phytoremediation promotion and inorganic pollutant biodegradation

Endophytes	Host plant(s)	Beneficial Features	Pollutant(s)	References
Enterobacter sp.	*Cannabis sativa* L *Arundo donasx* L	Plant growth regulation	Toxic elements (Cr, Ni and Cu)	Ferrarini et al. 2021
Pseudomonas fluorescens (PF01) *Bacillus subtilis* (BS01)	*Vigna radiata,* L	Plant growth regulation Increased biomass	Cadmium (Cd)	Rajendran and Sundaram 2020
Bacillus thuringiensis (PZ-1)	*Brassica juncea*	Plant growth regulation and siderophore production	As, Cu, Pb, Ni, and Zn	Yu et al. 2017
Consortia of bacteria	*Lupinus luteus*	Biodegradation	Toxic elements	Leroy et al. 2017
Fusarium sp. CBRF44, *Penicillium* sp. CBRF65, and *Alternaria* sp. CBSF68	*Brassica napus*	Plant growth regulation	Cd and Pb	Chen et al. 2016
Genetically engineered *Enterobacter* sp. CBSB1	*Brassica juncea SA*	Plant growth regulation	Cd and Pb	Peršoh 2015
Bacillus thuringiensis (GDB-1)	*Alnus firma*	Plant growth regulation	Pb, Zn, Cu, Cr and As	Babu et al. 2013
Mucor sp. MHR-7	*Brassica campestris L*	Plant growth regulation, Biodegradation, Metal extraction	Zn^{2+}, Mn^{2+}, Cr^{6+}, Cu^{2+}, Co^{2+}	Lemaire et al. 2012
Mucor sp. *selffusant* CBRF59T3	*Brassica napus*	Plant growth regulation, Metal extraction	Cd and Pb	
Pantoea stewartii ASI11, *Enterobacter* sp. HU38, and *Microbacterium arborescens* HU33	*Leptochloa fusca (L.) Kunth*	Plant growth regulation	U and Pb	Xie and Dai 2015
Phialocephala fortinii, Rhizodermea veluwensis, and *Rhizoscyphus* sp.	*Clethra barbinervis*	Plant growth regulation	Cu, Ni, Zn, Cd, and Pb	Chen et al. 2013
Pseudomonas azotoformans ASS1	*Trifolium arvense*	Stress alleviation	Cu, Zn, and Ni	Toju et al. 2018
Serratia marcescens PRE01	*Pteris vittata*	Stress alleviation	Cd(II), Cr(VI), and V(V)	Kaul, et al. 2012
Variovorax sp. *Micrococcus* sp. *Microbacterium* sp. *Pseudomonas* sp. *Microbacterium* sp. and *Microbacterium* sp.	*Noccaea caerulescens* and *Rumex acetosa*	Plant growth regulation	Mixed toxic elements	

comparison to the wild microbial strain results in a tenfold increase in volatile methylated arsenic gas extrusion (Chen et al. 2013). Huang et al. (2016) recently modified a strain of bacteria, *Pseudomonas aureginosa* strain Pse-W, which has high Cd^{2+} resistance and Cd^{2+} remediation ability. Following the adsorption of metallothioneins to the cell surface of the bacterial strain to attract Cd, the engineered strain demonstrated a significant ability to mobilise Cd. The results showed that inoculating the strain Pse-W increased Cd uptake in plant organs. The study demonstrated that Cd-contaminated fields can be realistically bioremediated more easily by the GE *Pseudomonas* strain than by wild strains. Table 5 shows examples of integrated PGPR bioremediation of toxic elements.

10 Considerations to improve phytoremediation efficiency in artificial wetlands

In the preceding sections of this review, a variety of plants, endophytes, plant-growth promoting rhizobacteria were presented. It is acknowledged that constructed wetland environments necessitate a diverse range of plant species. The choice of vegetation is predicated on the effluent type and composition that are to be treated. Additionally, when designing constructed wetlands, the efficiency of the bioremediation program may be impacted by the following factors that must be taken into account when determining the suitable plants and phytodegradation activity.

Table 5 PGPR with abilities of phytoremediation promotion and inorganic pollutant biodegradation

PGPR	Host plant(s)	Beneficial Features	Pollutant(s)	References
Burkholderia sp. HU001 *Pseudomonas* sp. HU002	*Salix babylonica*	Plant growth regulation and increased cadmium tolerance	Cd	Weyens et al. 2013
Paenibacillus sp. RM	*Tridax procumbens* (roots)	Broad-spectrum heavy metal resistance	As, Cu, Zn and Pb	Govarthanan et al. 2016
Pseudomonas koreensis AGB-1	*Miscanthus sinensis*	Increased plant biomass, increased expression of chlorophyll and enzymes	Cd, Pb, Cu, ZN and As	Babu et al. 2015
B. pumilus E2S2 *Bacillus* sp. E1S2 *Achromobactera* sp. E4L5 *Stenotrophomonas* sp. E1L	*Sedum plumbizincicola*	Plant growth regulation, increase in biomass and metal uptake	Cd, Zn and Pb	Ma et al. 2015
Rahnella sp. JN6	*Polygonum pubescens*	Plant growth regulation and metal tolerance and accumulation	Cd, Pb and Zn	He et al. 2013
Arthrobacter sp.	*Glycine max*	Heavy metal resistance and accumulation	Cd	
Pseudomonas sp.	*Medicago sativa*	Plant growth regulation, increased chlorophyll content, metal tolerance	Cr (VI)	Tirry et al. 2021
Microbacterium arborescens	*Leptochloa fusca*	Plant growth regulation and improved HM accumulation	Uranium (U) and Pb	Ahsan et al. 2017
Simplicillium chinense	*Phragmites communis*	Improved metal tolerance and accumulation	Cd and Pb	Jing et al. 2019
Pseudomonas lurida E0026	*Heilanthus annus* (roots)	Plant growth regulation and enhanced metal uptake	Cu	Kumar et al. 2021

10.1 Bioavailability and element mobility

Chemical composition and sorption characteristics of soil/sediments affect metal mobility and bioavailability (Kos et al. 2012). Toxic metal bioavailability affects phytoextraction's efficacy. For example, low bioavailability limits Pb phytoextraction (Ali et al. 2013). Due to toxic metals' strong binding to soil/sediment particles or precipitation, a large percentage of them are non-bioavailable and inaccessible to phytoremediating plants (Sheoran et al. 2011). Consequently, they remain persistent in the affected soil. Toxic metals in soils can be divided into three bioavailability groups: readily bioavailable (Cd, Ni, Zn, As, Se, and Cu); moderately bioavailable (Co, Mn, and Fe); and least bioavailable (Pb, Cr, and U) (Prasad 2003).

Interestingly, plants like *Poaceae* species secrete metal-mobilizing "phytosiderophores" into the rhizosphere (Reichman and Parker 2005) to solubilize toxic elements in soil. Natural and induced phytoextraction depend on plant bioaccumulation. Natural phytoextraction uses natural hyperaccumulators with a high metal-accumulating capacity and metal-tolerance (Baker et al. 2000). Induced phytoextraction involves adding a chelator or other chemical to the soil to promote metal solubility or mobilisation, allowing plants to absorb more metals. Metal phytoextraction's low bioavailability is mitigated by the discovery that chelate can increase metal translocation from soil to plants (Blaylock et al. 1999). Soil parameters and chelate type determine bioavailable metals in the soil matrix (Shen and Shi 2005). Increasing heavy metal bioavailability improves phytoextraction with the implication that toxic elements cannot bioaccumulate in such soil. Only a small percentage of soil toxic elements are soluble and absorbable by plants (Blaylock et al. 1999). Zinc and copper are plant-bioavailable toxic elements (Lasat 1999). Low bioavailability of toxic elements like Pb makes phytoextraction less effective (Wang et al. 2006). It is also possible to introduce organisms such as *Aspergillus, Penicillium, Gliocladium* sp. and *Candida* sp. into artificial wetlands to produce citric and gluconic acids which are known chelating agents (RoyChowdhury et al. 2018) which will increase bioavailability for phytoextraction.

A plant can increase metal bioavailability in many ways. Root exudates reduce soil pH, which encourages heavy metal desorption from insoluble complexes to generate free ions, raising soil heavy metal concentrations (Thangavel and Subbhuraam 2004). Plants can produce metal-mobilizing chemicals in the rhizosphere, such as phytosiderophores, carboxylates, and organic acids, which alter soil physicochemical characteristics and allow heavy metal chelation, enhancing solubility, mobility, and bioavailability (Padmavathiamma and Li 2012). Rhizosphere microorganisms increase plant heavy metal availability and absorption

(Vamerali et al. 2010; Sheoran et al. 2011). These microbes release enzymes and chelates into the rhizosphere, improving heavy metal absorption and translocation (Clemens et al. 2002). PGPR and plant growth promoting endophytes (PGPE) can improve the solubility of water-insoluble Zn, Ni, and Cu by secreting protons or organic anions (Becerra-Castro et al. 2011). PGPR release biosurfactants and siderophores to mobilise toxic elements. Siderophores, which chelate Fe^{3+}, also bind Cd, Ni, As, and Pb (Schalk et al. 2011). Chelating with toxic elements improves siderophore bioavailability to rhizobacteria and plants. In general, rhizobacteria are effective at making heavy metal ions accessible.

Endophytes aid plant Fe^{2+} uptake by producing low-molecular-weight (500–1500 Da) polar molecules. Endophytic siderophores bind Fe^{2+} and other bivalent metal ions. They help plants extract additional metal ions from soil and alleviate stress from excessive metal enrichment. They also help plants absorb Fe^{2+} in Fe^{2+} deficiency situations, improving plant health and growth.

10.2 Biostimulation (Nutrient supplementation)

Industrial effluents characteristically contain toxic elements and are devoid of growth nutrients and other essential elements. Diluting effluents to levels that living cells can tolerate promotes assimilation, but this strategy does not address the lack of nutrients needed to increase biomass and boost bioremediation efficiency. Apart from adding the major nutrients such C, H, N, O, S, and P; it is also important to encourage certain microbial interactions to provide for some of the essential nutrients or improve the bioassimilation from the environment. In situ bioremediation of metal-polluted effluents may benefit from the introduction and selected mixture of organic wastewater to improve nutrient content and promote growth. Plant-associated microbes boost plant growth in metal-polluted areas, regulate metal absorption and translocation, and increase metal bioavailability by secreting ligands and organic acids (Ma et al. 2016). Few studies have examined the bacterial communities associated with wetland plants, and even fewer have explained their reactions to mixed and contaminated settings (Syranidou et al. 2018). There are few data on how contaminants affect wetland plants' endophytic bacteria. Pollution type and quantity, plant species, biostimulating bacteria administration, or a multifactor combination may affect phytoremediation capacity and underlying endophytic assemblages. Previous research found that inoculating *Juncus acutus* with an endophytic bacterial consortium eliminated emerging pollutants and metals faster and more effectively than non-inoculated plants (Syranidou et al. 2016).

Whiting et al. (2001) found rhizosphere bacteria may mobilise zinc for *T. caerulescens* hyperaccumulation. Rhizosphere microflora increases water-soluble zinc in soils, allowing *T. caerulescens* to accumulate more zinc. When *Microbacterium saperdae*, *Pseudomonas monteilii*, and *Enterobacter cancerogens* were added to surface-sterilized *T. caerulescens* seeds in autoclaved soil, the zinc content in the shoots doubled over the axenic control. Another finding was that the concentration of selenium (Se) in sediment decreases as the flow channel in the wetland system descends. According to Zhang et al. (1997), carbon content is an essential factor controlling Se distribution in sediment, but dissolved Se input significantly affects this connection, showing that rhizosphere bacteria play an indirect role in metal bioaccumulation. PGP bacteria produce siderophores, which bind metals and increase their bioavailability in the rhizosphere (Gadd 2010). Siderophores are produced by a wide range of microorganisms, but they are more prevalent among PGP bacteria, which grow and produce siderophores best in harsh environmental conditions such as nutrient shortage or high heavy metal concentrations (Rajkumar et al. 2010). *P. aeruginosa* siderophores increased the concentration of Pb and Cr in the rhizosphere, making them available for maize absorption.

Moreover, PGPR bacteria produce low molecular weight organic acids like gluconic, oxalic, and citric, which aid heavy metal mobilisation and solubility. These organic acids help complex toxic elements, allowing plants to absorb them more easily (Ullah et al. 2015). *Gluconacetobacter diazotrophicus* can produce 5-ketogluconic acid, a gluconic acid derivative that solubilizes Zn compounds. PGP bacteria produce biosurfactants that boost metal mobilisation and phytoremediation. Microbe-produced biosurfactants form complexes with toxic elements at the soil interface, desorbing metals and increasing solubility and bioavailability (Rajkumar et al. 2012). Juwarkar et al. (2007) mobilised Pb and Cd using *Pseudomonas aeruginosa* BS2 biosurfactants. Heavy metal stress activates phytochelatein (PC) synthase, produced by certain bacteria. These enzymes bind to toxic elements, especially Cd, via thiolate complexes, increasing metal mobility and availability (Kang et al. 2007).

Heavy metal detoxification must precede phytoremediation (Thakur et al. 2016). Plants often avoid or tolerate heavy metal toxicity. Plants use one of two strategies to keep heavy metal concentrations below toxicity levels (Hall 2002). Microorganisms influence metal mobility, toxicity, and bioavailability. Although, there are significant research on the microbial detoxification processes, there remains aspects that are poorly understood. Understanding the microbial mechanisms that control metal removal in wetlands can improve their long-term efficacy (Kosolapov et al. 2004).

10.3 Bioaugmentation

Bioaugmentation improves an existing microbial population by adding cultivated, sometimes specialised microorganisms

(Kurniawan et al. 2022). Bioaugmentation is available in many forms. Current and historical information about contaminated places influences strategy selection. Some contaminants are recalcitrant, requiring two or more bioaugmentation approaches for complete removal. Nwankwegu et al. (2022) described some bioaugmentation types. For example, indigenous microorganisms or the use of exogenous microorganisms (either pure cultures of recognised microorganism species or strains or a collection of distinct microorganisms to build a high-density cell mass called a microbial consortium) to increase cell density, and the use of genetically altered microbes (recombinant microbes). Microorganisms are chosen based on their ability to break down contaminants and withstand various environmental conditions. It is known that bacteria, fungus, yeast, actinomycetes, and algae can survive in a variety of environments and remove toxic elements from polluted areas (Purwanti et al. 2018).

Bioaugmentation by introducing indigenous and exogenous microbes that can tolerate and minimise heavy metal effects is a well-known method of remediating heavy metal contamination (Purwanti et al. 2020). Several studies showed that bioaugmentation is more suitable for treating heavy metal-containing wastewater because the formed stable metal can be quickly separated from the wastewater by accumulating it at the bottom of the treatment area, resulting in complete separation between phases (water and metal) (Shahid et al. 2020) allowing for the introduction of specialised microorganisms.

Additionally, some studies have demonstrated bioaugmentation's effectiveness in treating heavy metal-polluted soil, but its practicality in real-world applications is questioned (Kurniawan et al. 2022). Recent studies found that bioaugmentation degraded pollutants in > 90% of organically damaged environments (Dalecka et al. 2021; Muhamad et al. 2021). However, most of the protocols were executed under controlled laboratory conditions using simulated organic pollutants. Concerns were raised about the application of these approaches in real-scale contaminated sites, specifically the separation of accumulated metal from soil, to create a remediated clean medium free of hazardous toxic elements (Purwanti et al. 2019). These challenges can easily be addressed by constructing prototypes and monitoring trends over a period of time. However, the major obstacle remains cost, as ideal prototype test sizes are relatively expensive to construct.

Other pertinent issues that need consideration include the problem of exogenous microorganisms' population decrease after being introduced, due to the rigorous adaptation necessitated in the new environment. Environmental and biotic challenges can destroy imported species. Abiotic stressors include temperature, water, pH, nutrient, and pollutant variations (Steinle et al. 2000). Other challenges include competition for limited resources from native species and antagonistic interactions like antibiotic synthesis by competitive organisms and predation by protozoa and bacteriophages. Getting inoculant to the right place can be difficult (Dong et al. 2002). Distribution of microorganisms often rely on mechanical processes. Fungi, proliferation and distribution are usually limited to surface applications, while bacteria can adapt to subsurface or surface uses (Nwankwegu et al. 2022). Therefore, upscale artificially constructed wetlands must consider these challenges within the design.

In summary, considerations to ensure successful bioaugmentation regimes must include prior comprehensive understanding of specific physico-chemical properties of the bioprocess that are linked to poor bioreactor performance, such as: (i) an understanding of the ecological foundation of the microorganisms; (ii) developing techniques for monitoring successional patterns and interspecific interactions within the consortia; (iii) developing a flexible selection criteria; (iv) developing an inoculation strategy; (vi) developing a strategy where necessary for specific gene transfers; and (v) evolving operational and plant management strategies to tackle various challenges as they arise.

10.4 Genetically modified plants and invasive species

Over the years, advances in genetic engineering practise have made it possible to transfer desirable genes to plant species for the phytoremediation process. One of the primary goals of transforming plants with exogenous DNA is to improve heavy metal tolerance and accumulation (Rascio and Navari-Izzo 2011). A candidate macrophyte for phytoremediation must have several characteristics, including a) high biomass production that is adapted to the local and target environment, b) rapid growth, and c) a well-defined transformation protocol.

Plant genetic modification aims to increase the expression of genes encoding uptake, translocation, heavy metal sequestration, and antioxidant activity (Das et al. 2016). According to research, the relationship between antioxidant activity and heavy metal tolerance is directly proportional, as the presence of toxic elements triggers the synthesis of ROS, which causes oxidative stress. Increasing heavy metal tolerance will thus necessitate a strategy to boost antioxidant activity, which can be accomplished by inserting genes that constitutively express the antioxidant machinery (Kozminska et al. 2018). It is technically preferable to modify fast-growing, high biomass plants to increase heavy metal tolerance and uptake rather than forcing hyperaccumulators to increase biomass production. Although hyperacumulators are excellent candidates for phytoremediation, the vast majority are low biomass plants. It is now possible to insert the necessary genes or hyperaccumulation traits into high biomass producing plants using genetic engineering methodologies.

Plant genes that encode heavy metal transporters are typically represented by large gene families. They are potential candidate genes for transformation toward improved phytoremediation potential. Manipulation entails increasing metal accumulation in either the roots or the shoots for phytostabilization or phytoextraction. A plant's biomass production and bioconcentration efficiency are two factors that contribute to its efficiency as a phytoextractor (bioconcentration is the ratio between the concentration of the contaminant in the harvestable parts of the plant and its concentration in the soil). To improve heavy metal accumulation, genes encoding heavy metal/metalloid transporters can be transferred and overexpressed in target plants. Metal ion transporters such as ZIP, MTP, MATE, and HMA family members can be engineered using metallothionein, phytochelatins, and metal chelators genes. These metal chelators function as metal-binding ligands, assisting in heavy metal uptake and root-to-shoot translocation, and controlling the intracellular movement of heavy metal ions in organelles. Heavy metal uptake and translocation can be improved by overexpression of genes encoding natural chelators (Wu et al. 2010). Clemens et al (1999) conducted one of the first studies in this area, screening for plant genes involved in the mediation of metal tolerance, specifically finding the gene for cadmium tolerance, and then applying recombinant technologies to *Arabidopsis* and *S. pombe* genes to increase metal tolerance. This method has been replicated in several studies to date (Zhu et al. 2021; Kumar et al. 2019; Qiao et al. 2019).

Although genetic engineering of wetland plants has promising prospects for improving plant performance in heavy metal phytoremediation, the technology has several drawbacks. Higher order organisms are frequently composed of many genes that encode one trait; similarly, mechanisms of heavy metal detoxification and accumulation involve a number of genes. Therefore, it becomes costly and time consuming to try and manipulate multiple genes to enhance the desired traits, with most studies failing. Furthermore, serious ethical concerns limit the use of G-E in phytoremediation research. As a result, field studies may be impractical, particularly for natural wetlands. The introduction of foreign (exogenous) DNA into a system can alter wetland dynamics. Because of its genetic advantage, an invasive species with foreign DNA would compete for resources with native species and eventually take over. As a direct consequence, obtaining approval for field testing in some areas may be difficult, the legitimate concern being the cascading effect on the food chain and ecosystem safety. The same argument can be made for alien species, though their proliferation has increased in the last decade, and some authors have demonstrated their capabilities in metal sequestration, as shown in Table 6. Although, the categorisation of plants as invasive is subjective and country-based, and it is often linked to the adjudged danger it poses to the natural biodiversity and the competitive advantage such alien species may pose to indigenous plants that could lead to possible extinction. Nonetheless, once these invasive species are present they tend to be very difficult to eradicate, thus some researchers have now investigated these alien species for possible utility within these new environments. Table 6 focuses on invasive species identified mainly in South Africa. We consider these species as useful for in situ bioremediation programs where they can be cultivated in a controlled environments and disposed-off using incineration or as feedstock in biogas digesters. This will prevent escape into natural water bodies.

10.5 Artificial wetland constructions

Constructed wetlands (CWs) are engineered systems that are designed and developed to mimic naturally occurring wetland processes (Stefanakis et al. 2014). CWs tend to have one major feature that differentiate them from conventional wastewater treatment facilities: this is the addition of large wetland plants, which include angiosperms and ferns, aquatic mosses, and large algae with easily observable tissues and are collectively known as macrophytes (Omandi and Navalia 2020). These macrophytes proliferate on beds filled with appropriate substrate, mostly in the form of natural media sand and gravel, allowing plants to develop an intricate root system that can penetrate and coalesce (Sehar and Nasser 2019) as shown in Fig. 2. The aquatic plants are grouped together based on their associated microbial assemblages (Hassani et al. 2018; Clairmont et al. 2019; Chowdhury et al. 2020; Deutsch et al. 2021).

It is possible at the storage area for untreated effluent to implement biostimulation (nutrient supplementation) to promote the growth of microorganisms that benefit from the essential nutrients addition when the untreated effluent is deficient in these nutrients. The sand and gravel act as stabilizers and adhesion surfaces. The choice of plant can factor the type and composition of effluent, where effluents is observed to contain metals that are not readily soluble of biologically available, chelating agents may be added or endophytic siderophores to enhance mobility and absorption leading to removal of metals. Plants may be removed in time, once, they have reached absorption capacity and can no longer uptake metals or have died due to the toxicity. These plants can be destroyed and replaced with fresh plants. The same can be done with invasive and genetically modified plants as the space is confined and plant growth can be controlled.

Constructed wetlands were initially employed in the treatment of domestic wastewater (Saleh et al. 2015); however, in recent years, the potential has been expanded to include industrial wastewater (Kaushal et al. 2018), storm-water

Table 6 Some alien aquatic plant species that have been applied in constructed wetlands (CW) systems for their phytoremediation abilities in South Africa

Macrophyte species and common name	Family	Type of macrophyte	Invasion status*	Natural distribution	Heavy metal uptake	N and P uptake	Best suited CW system	References
Azolla filiculoides Lam. (Red Water Fern)	Azollaceae	Free-floating	Invasive Category 1a	South America	Absorption of Fe, Cu, Ni, Pb, Zn, Mn and Cr	↑P	FWS	Hill and Coetzee 2017; Hill et al. 2020
Myriophyllum aquaticum (Vell.) Verdc. (Parrot's Feather)	Haloragaceae	Rooted emergent	Invasive Category 1a	Central and South America	Cd, Cu, Pb, Zn accumulation	↑ N lower than water lettuce, but similar ↑ P	SSF (VF/ HF)	Hill and Coetzee 2017; Hill et al. 2020
Pistia stratiotes L. (Water Lettuce)	Araceae	Free-floating	Invasive Category 1a	Pantropical	Absorption of Fe, Zn, Cn, Cr and Cd	↑ N and ↑ P	FWS	Hill and Coetzee 2017; Hill et al. 2020
Eichhornia crassipes (Mart.) Solms. (Water Hyacinth)	Pontederiaceae	Free-floating	Invasive Category 1a	South America (Amazon basin)	Absorption of (Fe, Zn, Cu, Cr and Cd)	↑ N and ↑ P	Hybrid	Hill and Coetzee 2017; Hill et al. 2020; Nazir et al. 2020
Salvinia molesta D.Mitch. (giant salvinia/Kariba Weed)	Salviniaceae	Free-floating	Invasive Category 1a, but proposed category 1b	South and Central America	Absorption of Ni, Cr and Cd	↑ N and ↑ P	Hybrid	Hill and Coetzee 2017; Hill et al. 2020
Sagittaria platyphylla (Engelm). J.G. Sm (Delta arrowhead)	Alismataceae	Rooted emergent	Category 1(a)	U.S.A	-	↑ P	FWS	Henderson and Wilson 2017; Ndlovu 2020
Pontederia cordata L. (Pickerelweed)	Pontederiaceae	Rooted emergent	Category 3	Eastern U.S.A; Central and South America	Accumulation of Cd	↑ N and ↑ P	FWS	SANA 2018, Xin et al. 2020
Iris pseudacorus L. (Yellow Flag)	Iridaceae	Rooted emergent	1a	Asia, Europe and North Africa	Accumulation of Pb, Cd Cu, Mn, Hg, As, ZN, Ni, Fe	↑ N and ↑ P	FWS	Branković et al. 2015; Parzych et al. 2016
Egeria densa Planch. (Brazilian Waterweed)	Hydrocharitaceae	Submerged	Category 1 but proposed cateogry 1b	Brazil and coastal Argentina and Uruguay	Cd, Cu Fe, Pb, mn, Zn	↑ N and ↑ P	SSF (HF)	Thomaz et al. 2015, Mgobozi 2014
Hydrilla verticillata (L.f.) (Royle Hydrilla)	Hydrocharitaceae	Submerged	Category 1a	Asia, N-E Australia and India	Accumulation of Cd, Pb, Ni,	↑ N	SSF (HF)	Al-Tabatabai 2020; Zhang et al. 2020
Salvinia minima Baker (Common Salvinia)	Salviniaceae	Free floating	Category 1b	Central and South America and West Indies	Absorption of Cd, Pb, Ni, Zn, Cr (VI)	↑ N and ↑ P	FWS	Iha and Bianchini 2015; Prado et al. 2021
Azolla cristata Kaulf. (Mexican Azolla)	Azollaceae	Free floating	Category 1b	North, South and Central America	Absorption of Cr, Pb, Zn, Hg, Cu, Ag, Ti	↑P	FWS	Hassanzadeh et al. 2021

Table 6 (continued)

Macrophyte species and common name	Family	Type of macrophyte	Invasion status*	Natural distribution	Heavy metal uptake	N and P uptake	Best suited CW system	References
Nymphaea mexicana Zucc. (Mexican Water Lily)	Nymphaeceae	Rooted floating	Category 1b	Southern U.S.A and North Mexico	Accumulation of Cd,	↑ N and ↑ P	SSF (VF)	Schor-Fumbarov et al. 2003
Cabomba caroliniana A.Gray. (Fanwort)	Cabombaceae	Submerged	Category 1a	U.S.A	Accumulation of Cd,	↑ N	SSF (HF)	Robertson et al. 2012; Kassin et al. 2015
Nasturtium officinale W.T. Aiton (Watercress)	(Brassicaceae	Rooted emergent	Category 2	Europe	Accumulation of Cd, Zn, Cu, Pb	↑ N and ↓ P	FWS	Khan et al. 2022
Hydrocleys nymphoides (Humb. and Bonpl. Ex Willd.) Buchenau-Water Poppy	Alismataceae	Rooted floating	Category 1a	Tropical America	-	↑ N and ↑ P	SSF (HF)	Nxumalo et al. 2016; Hill and Coetzee 2017; Hill et al. 2020
Sagittaria latifolia Willd. (Broadleaf Arrowhead)	Alismataceae)	Rooted emergent	Category 1a	North America	Absorption of Mn, Zn	↑ N and ↑ P	FWS	South Africa 2020:1020; Hill and Coetzee 2017; Hill et al. 2020
Nymphoides peltata (S.G.Gmel.) Kuntze-Floating Heart	Menyanthaceae	Rooted floating	Category 1a	Algeria	Absorption of Cu, Zn, Mn, Co, Pb, V	↑ N and ↑ P	SSF (HF)	South Africa 2020:1020, Bai et al. 2018; Hill and Coetzee 2017; Hill et al. 2020
Lythrum salicaria L. (Purple loosestrife)	Lythraceae	Rooted emergent	Category 1, but proposed category 1	Europe and Asia	Accumulation of Ni, Cu, Pb	↑ N and ↑ P	FWS	Nicholls and Tarun 2003; Bingöl et al. 2017

*Invasion status keys according to the National Environmental Management: Biodiversity Act (NEMBA), Act 10 of 2004) preceded by Conservation of Agricultural Resources Act (CARA) (South Africa 2020)

Category 1a: Invasive species that require immediate control. These invasive species need to be destroyed and eradicated from the environment as no permits for cultivation will be dispensed

Category 1b: Invasive species that require immediate control as part of an invasive species control programme. These represent the most widespread and troublesome species. These species are placed under the government sponsored invasive species management programmes and no permits for propagation will be issued

Category 2: Invasive species regulated by area. Demarcation notice is required for import, possession, growth, breeding, moving, selling, or buying as a gift of any plants listed as Category 2 plants and plants need to be controlled outside the specified areas for cultivation. No permits will be issued to persist in riparian zones

Category 3: Invasive species regulated by activity. An individual permit is required to perform of the following: import, possess, growth, breed, move, sell or buy involving a cat 3 species. No permits will be issued for category 3 invasive to exist in riparian zones, except for permitted Category 2 species

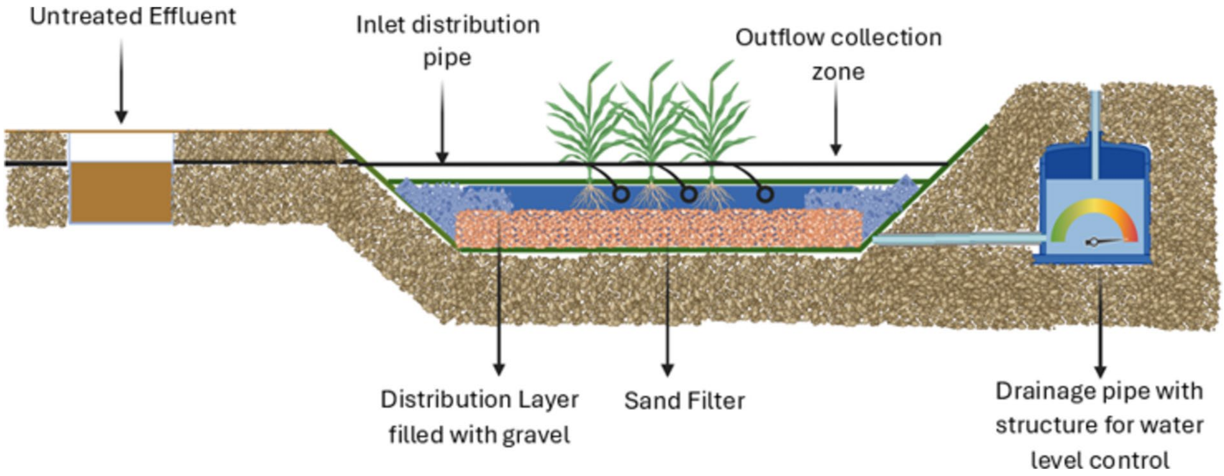


Fig. 2 Constructed wetland

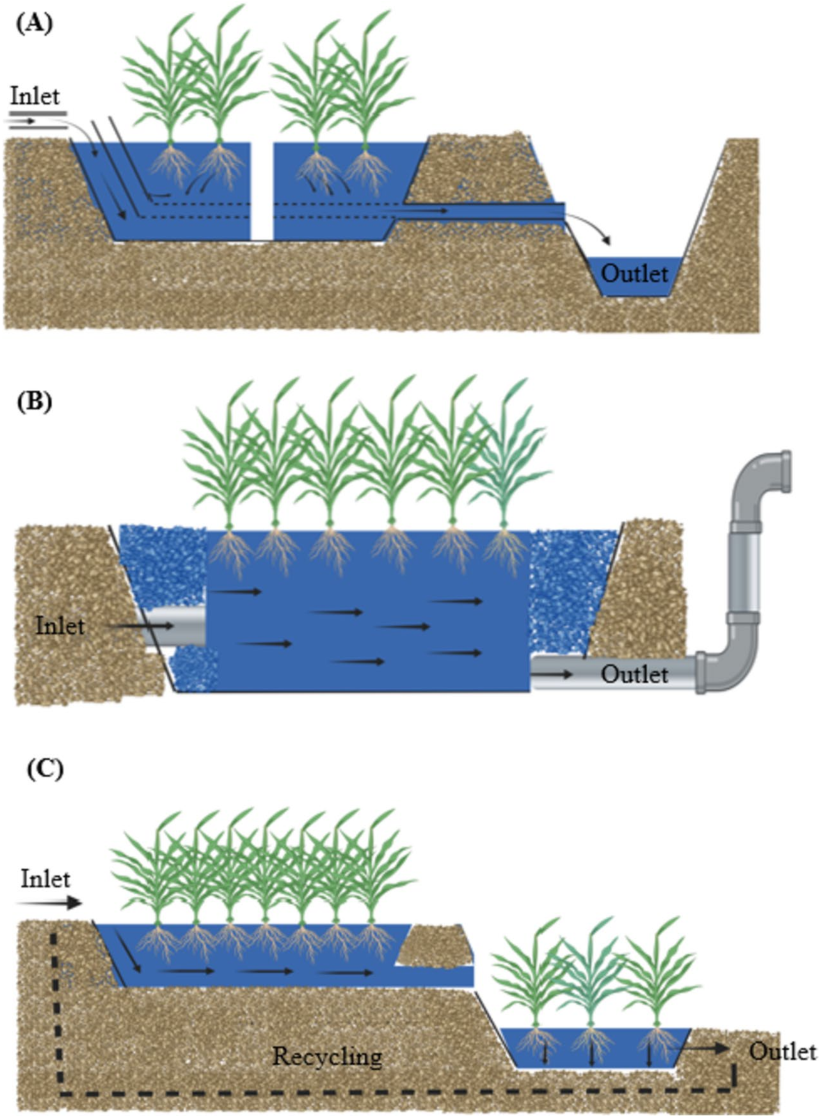
runoff (Guo et al. 2014), agricultural wastewaters (Wang et al. 2018), and landfill leachate (Madera-Parra and Ríos 2017). Because of the higher concentration of pollutants in the influents, the use of CWs for industrial wastewater treatment remains difficult (Stefanakis 2018). Through a series of processes and mechanisms, CWs with macrophyte plant roots, aquatic microbial communities, and supporting mineral matter are effective at removing various pollutants present in wastewater such as nitrogen, phosphorus, and organic matter (Stefanakis et al. 2014). Advances in phytoremediation using CWs have focused on the remediation of various organic micro-pollutants, such as phenolic compounds (Omandi and Navalia 2020), as well as inorganics from pharmaceuticals, such as endocrine disrupting chemicals (EDCs) and toxic elements (Daley and Kucera 2014). The adaptation of this treatment technology has gained interest around the world, particularly in economically underdeveloped countries with water scarcity challenges (Omandi and Navalia 2020). Kenya and Tanzania, for example, use large-scale CWs to treat municipal and industrial wastewater. In Kenya, a hybrid wetland (horizontal subsurface and surface flow) is commonly used (Makopondo et al. 2020). However, more evidence on the development of wetland technologies in Africa is limited. Figures 3A-C shows the basic types of constructed wetland types.

Applying wetland hydrology, constructed wetlands are classified based on various parameters. Water flow regime (surface and subsurface) and macrophyte growth (emergent, submerged, free-floating, and floating-leaved plants) are the most important factors (Lamori et al. 2019). These factors are thought to be important in the biodegradation and biochemical transformation of various carbon sources and pernicious compounds (Sehar and Nasser 2019). The quality of the system's effluent is known to improve as the system's complexity and modifications increase (Vymazal and Kröpfelová 2008). Wetlands of various types are possible during wastewater treatment using CWs, including free water surface flow (FWSF) wetlands, subsurface flow (SSF) wetlands, and hybrid systems (HS). SSF is further classified into two types: horizontal flow SSF (HSSF) and vertical flow SSF (VSSF) (Biswal and Balasubramanian 2022). At the same time, the vegetation species used is an important parameter that further divides CWs into three major types: 1) emergent macrophyte CW, 2) submerged macrophyte CW, and 3) floating treatment wetland (FTW) systems, with rooted emergent macrophytes receiving the most attention (Stefanakis 2016). Table 7 provides some of the merits and draw backs of the various constructed wetlands designs. Table 8 summarises some of the removal efficiency observed with the use of different macrophytes in various constructed wetlands. It should be noted that temperature and climate conditions are important factors in plant development and growth (Raza et al. 2019).

11 Future perspectives

The current approach to enhancing the phytoremediation capabilities of macrophytes for the in-situ removal of industrial pollutants in a CW remains an ongoing endeavour. As the likelihood of floods and droughts increases in specific regions, climate change has emerged as a crucial factor to contemplate in designing CWs. Therefore, the efficacy of remediation programs will be influenced by the choice of plants, the function of CWs, and their incorporation into design methodologies. The integration of artificial intelligence and machine learning in conjunction with sensing technology that can simulate various conditions and potential adverse weather events is expected to optimize design

Fig. 3 Basic types of constructed wetlands. **A** Vertical Flow (VF) constructed wetland; **B** horizontal flow (HF) constructed wetland; and **C** hybrid flow constructed wetland



parameters, enabling the system to respond appropriately (Singh et al. 2023).

At present, the process of bioremediating pollutants is predominantly conducted by microbial consortiums, which rely on the sequential production of enzymes by microorganisms to degrade complex compounds. The prediction of microbial population shifts over time by microbial succession indicates that the degradation community is in a constant state of flux. In contrast, the toxicity of polluted water is known to suppress the proliferation of microorganisms, often delaying the degradation process due to the necessary adaptation and acclimation periods. This has frequently been regarded as an inadequacy of the biological process, given the need for rapid toxic element removal. Nevertheless, the consistent advancements in functional omics, as well as our ability to identify plant and microbial species and genes involved in toxic element removal processes through expanding organism databases, will reduce the time lag for biological processes. This will enable the implementation of more targeted bioremediation programs. Phytoremediation processes will be enhanced by the accelerated access to references of novel enzymes on these data bases and the potential for synthesis. Furthermore, this will facilitate the identification of a greater variety of plant species with specialized phytodegradation functions, thereby enhancing our capacity to select and optimize pollution remediation processes (Wang et al. 2022).

The comprehension of plant responses to nanoparticles is a critical area of research as nanotechnology increasingly finds application in everyday life. It is imperative to recognize that they will evolve into the contaminants of the future. Hence, a comprehensive assessment of plant participation in nanoparticles removal from the environment and the underlying processes of migration, absorption, transformation,

Table 7 The advantages and disadvantages of various constructed wetland systems (Gorgoglione and Torretta 2018; Biswal and Balasubramanian 2022)

Constructed Wetland types	Advantages	Disadvantages
Surface flow	On a cost per unit basis, it is cheap and construction designs are simple	Lower rates of contaminant removal per unit of land than SSF wetlands = more land to obtain same level of treatment as SSF wetlands
	Can be applied towards higher suspended solids wastewaters	Needs more land than traditional treatment methods
	Provides greater flow control than SSFW	Threat of ecological and human exposure to surface flowing wastewaters
	Offers more diverse wildlife habitat	Poor nitrification owning to anoxic environment
	Less requirements on energy, mechanical equipment and skilled persons	Less tolerant to cold climates
	Perfect integration into land scape	Mosquito production due to large open area
	Green space with the environment	Exposure to odour and insects due to free/ open water surface
Subsurface flow	Tolerant to cold climate	Less attractive to wildlife
	Higher assimilation rates	Low denitrification (VF)
	Good nitrification and denitrification	Short flow distances (VF)
	Longer life cycle	Demand for high technical expertise (VF)
	Hydraulics are simple	Plugging due to high SS of wastewaters
	Minimise land requirement	More expensive to construct than SF on cost per acre basis
	High treatment efficiency from start	Higher lag requirement (HSF)
HSSF	Long flowing distances possible; nutrient gradients can be established	Higher area demand
	Nitrification and denitrification possible	Equal wastewater supply is complicated
	Formation of humic acids from N and P removal	Careful calculation of hydraulics necessary for optimal O_2-supply
	Longer life cycle	
VSSF	Smaller area demand	Short flow distances
	Simple hydraulics	Poor nitrification
	High purification performance from the start	Higher technical demand
		Loss of professional especially P removal (saturation)

and accumulation capacities is crucial for proactive management of nanoparticles as waste. Thus, such insights will enhance our readiness to confront this possibility.

12 Conclusion

Macrophytes are considered an important component of the wetlands ecosystem not only as the habitat and energy source for aquatic life but, also for their capability to improve the quality of water by absorbing nutrients and inadvertently pollutants via their effective root systems and to function as powerful biofilters. The surge in industrial activities have resulted in the introduction of various organic and inorganic pollutants in aquatic systems, causing cascading effects on biodiversity and human health. Conventional remedial strategies have been implemented to eradicate these pollutants from the environment; however, with varying degrees of success. Phytoremediation has gained acceptance as an environmentally sustainable practice for removing pollutants from various wastewaters. Aquatic macrophytes when hosting endophytes benefit from their presence as they aid in plant growth as well as for the degradation of pernicious compounds via complex biochemical processes. Both endophytes and rhizospheric bacteria form these synergistic interspecific interactions that can be tailored to treat specific profile of industrial effluents. Such treatment regimens are best controlled in situ. Therefore, constructed wetlands can be readily applied. More recently, invasive macrophytes are being considered due to their numerous advantages obtained through evolution and adaptation. The prospect of such technology relies on optimising parameters such as finding out the best macrophyte-microbial assemblage to carry out pollutant degradation, broadening the investigation of hyperaccumulators for heavy metal remediation, as well as evolving strategies in retrofitting existing CWs with

Table 8 Macrophytes and their degradation of various industrial pollutants using different CW systems

Macrophyte used	Wetland system type	Pollutant	Removal efficiency	References
Phragmites australis *Typha latifolia*	Surface flow	Cd, Cu, Pb and Zn	5%, 60%, 31%, and 86%	Gill et al. 2017
Phragmites karka *Cyperus alternifolius* *Typha domingensis* *Borassus aethiopum*	Horizontal subsurface flow	Cr	*P. karka* – 97.7% *C. alternifolius* – 98% *T. domingensis* – 99% *B. aesthiopum* – 99.3%	Tadesse and Seyoum 2015
Eichhronia crassipes *Pistia stratiotes*	Lab scale (surface flow) in plastic containers	Pb	*P. stratiotes* (0.063 mg/L) has better metal removal efficiency > *E. crassipes*	Jamion et al. 2021
Typha domingenesis *Pistia stratiotes* *Eichhornia crassipes*	Horizontal subsurface flow	Textile effluent	*T. domingensis* – Good in undiluted effluent *P. stratiotes* – Poor *E. crassipes* – Poor	Shehzadi et al. 2016
Heliconia rostrata *Eichornia crassipes*	Vertical subsurface flow Surface flow	Ibuprofen Caffeine	Ibuprofen – 95% Caffeine – 83%	De Oliveira et al. 2019
Washingtonia robusta *Nerium oleander* *Typha latifolia* *Cyperus papyrus* *Canna indica* *Lolium perenne* *Juncus eusus*	Horizontal subsurface flow	BOD, COD, TC and NH3, NH4, Pathogenic bacteria	BOD: 80–95% COD: 94% TSS: 60% NH3 and NH4: 50% Total coliform bacteria and Streptococci): 99%	Saggaï et al. 2017
Canna flaccida	Surface flow	Acetaminophen, Carbamazepine	Acetaminophen – 100% Carbamazepine – 73–81.8%	Hwang et al. 2020
Phragmites australis	Subsurface vertical flow	Ag	78.53%	Bao et al. 2019
Phragmitis australis	Subsurface vertical flow	Ce	17.9%	
Eichhornia crasipes *Pstia stratiotes* *Rhizophora mucronata* *Bruguiera gymnorrhiza* *Sargassum wightii* *Kappaphycus alvarezii*	Subsurface vertical flow	Cu and Zn	*K. alvarezii*: Zn–76.06% Cu–16.64% *S. wightii*: Zn–17.6% Cu–1.96	Mahesh et al. 2020
Nymphaea amazonum *Eleocharis mutata*	Surface flow	Imidacloprid Cyhalothrin	Imidacloprid: *N. amazonum*: 75% *E. mutata*: 15% Cyhalothrin: *N. amazonum* and *E. mutata*: < 1%	Mahabali and Spanoghe 2014
Eichhornia crassipes	Surface flow (laboratory scale)	Hexavalent chromium (Cr IV)	-	Saha et al. 2017
Eleocharis acicularis	Floating and pot treatment(field experiment)	Mine tailings (Mn, As, Cu, and Pb)	BCFw > 100 for Mn, As, Cu, and Pb	Sakakibara 2016
Lemna minor	Lab scale (plastic containers)	Synthetic leachate and dumpsite leachate	Higher rates of reduction of COD and nutrients for dumpsite leachate N and P removal from synthetic leachate was greater: 16% for N and 35% foe P	
Heliconea Zingiberales *Cyperus Haspan*	Horizontal Flow	Carbamazepine Sildenafil Methylparaben	95% 97% 97%	Vystavna et al. 2017

Table 8 (continued)

Macrophyte used	Wetland system type	Pollutant	Removal efficiency	References
Typha latifolia *Cantella asiatica* *Impoea aquatica* *Eichhornia crassipes* *Bacapa mannieri*	Lab scale (1L glass bottle)	AMD	*I. aquatica* Neutralises AMD, pH increased by 81%	Osa and Apuan 2018
Trapa natans *Salvinia cuculata Roxb*	Floating surface (batch cultures)	Industrial wastewater	55 mg/L	Alam and Hoque 2017
		BOD	33.32 mg/L	
		COD	50	
		Nitrate	31.25	
		Ammonium	77.27	
		TP	43.02 mg/L	
		BOD	31.04 mg/L	
		COD	Nitrate: 20	
		Nitrate	5.26	
		Ammonium	81.25	
		TP		
Salvinia molesta *Lemna minor* *Ceratophyllum demersum* *Elodea canadensis*	Surface flow	Diclofenac	99%	Nivala et al. 2019
		Triclosan	96–99%	
		Naproxen	45–53%	
		Ibuprofen	33–48%	
		Caffeine	81–99%	
Phragmites australis *Typha latifolia* *Scirpus sylvaticus L*	Vertical flow	Naproxen	80%	Chen et al. 2016
		Propranolol	80%	
		Paracetamol	50%	
		Caffeine	50%	
Eichornia crassipes	Surface flow	Ibuprofen	97%	Hwang et al. 2020
Myriophyllum verticillatum *Pontederia cordata*	Hybrid System	Steroid hormones	97%	Matamoros et al. 2017
		biocides	92%	
Carex. cuprina (Sandor ex Heuff.) Nendtv. ex A. Kern *Alisma lanceolatum* *Epilobium. hirsutum L* *Iris pseudacorus L* *Juncus. inflexus L*	Horizontal flow (microcosm)	Metallic pollutant cocktail: Al, Cd, Cr, Fe, Mn, Ni, Pb, Sn, Zn, PHE, PYR, THC, Anionic Detergent LAS	Results are extensive (5 plants with 12 elements each)	Guittonny-Philippe et al. 2015
Eichhornia crassipes *Pistia stratiotes* *Hydrocotyle umbellate*	Lab scale (Plastic tubes)	Battery industry effluent)	93%	Rashid et al. 2020
		Cu	100%	
		Cr	100%	
		Pb	86%	
		Cd	100%	
		Cu	100%	
		Cr	98%	
		Pb	100%	
		Cd	85%	
		Cu	100%	
		Cr	85%	
		Pb	100%	
		Cd		
Typha latifolia *Eichhornia crassipes* *Lemna gibba* *Pistia stratiotes*	Hybrid System	Cd	60–96%	Engida et al. 2020
		Cu	82–90%	
		Pb	78- 97%	
Pistia stratiotes	Lab scale (glass containers)	AMD (Cu)	COD: 5 mg/L = 92.45% COD: 7 mg/L = 88%	Novita et al. 2019

appropriate types of macrophytes. Moreover, in controlled in situ environments, it is possible to investigate and apply novel candidate genes for insertion into hosts to improved various enzyme expression and in this way increase degradation efficiency. Such application should take ethical issues into consideration and plan to ensure confinement of these alien species and novel genes and/or transformed plants and organisms to avoid their introduction to natural wetlands or other environments.

Acknowledgements The authors wish to acknowledge the immense assistance consistently provided by Ms. Ramaisimela Dolly Mazwi as an administrative staff of the University of South Africa.

Author contributions G.N.I. conceptualized the research; the original draft preparation was executed by T.L and T.M; manuscript draft edits and improvement was done by G.N.I. Final draft edit was done by T.N.M. All authors contributed to the several drafts' corrections and editing to achieve a final draft. All authors have read and agreed to the published version of the manuscript.

Funding Open access funding provided by University of South Africa. This research received no direct funding.

Declarations

Conflicts of interest The authors declare no conflict of interest.

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