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Phytoremediation in sustainable wastewater management: an eco-friendly review of current techniques and future prospects

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ABSTRACT

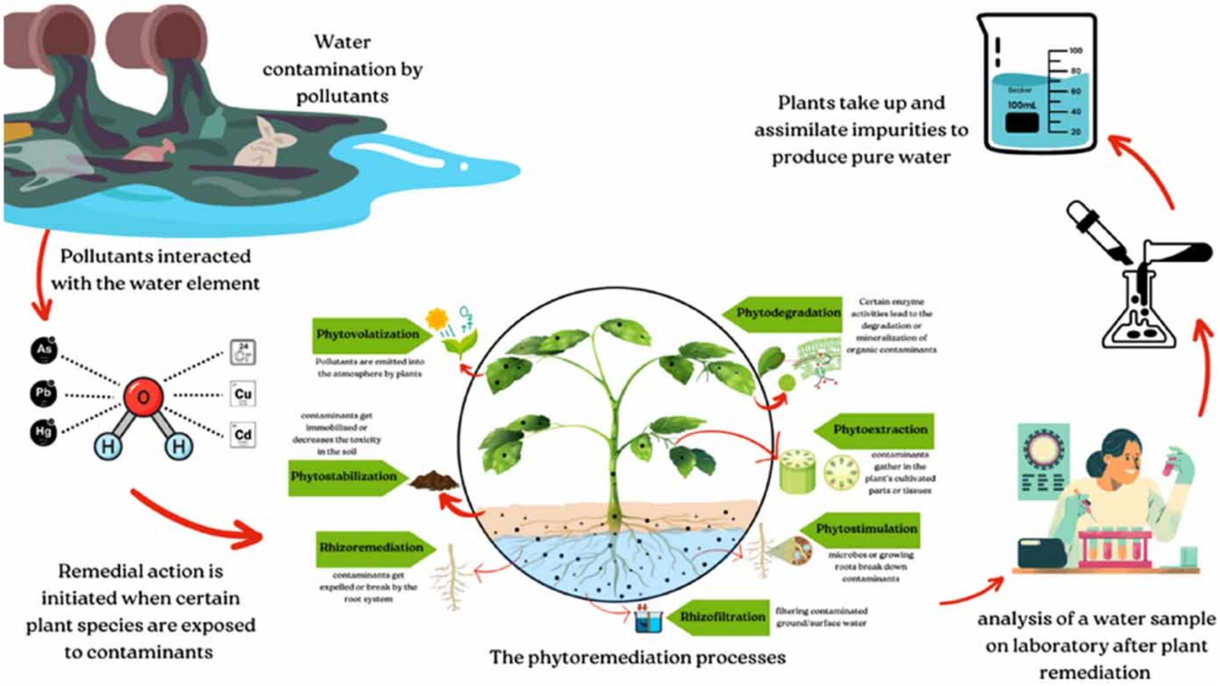
The sustainable wastewater treatment method known as phytoremediation is reviewed in this paper, with particular attention paid to important technologies including phytoextraction, rhizofiltration, phytostabilization, phytodegradation, and phytovolatilization. The study emphasizes the effectiveness of phytoextraction for heavy metal contamination using hyperaccumulator plants. It also highlights the versatility of phytoremediation by presenting compelling case examples in various situations. This environmentally friendly strategy offers affordable answers to the worldwide water pollution challenge and is in accordance with the growing demand for environmentally aware techniques. Phytoremediation – which emphasizes methods like phytoextraction – becomes a more viable path forward for wastewater pollution mitigation as environmental stewardship advances. By fusing theoretical understanding with real-world implementations, the article advances the conversation on sustainable wastewater treatment while reinforcing phytoremediation's promise for a more environmentally friendly future.

Key words: phytodegradation, phytoextraction, phytoremediation, phytostabilization, phytovolatilization, rhizofiltration

HIGHLIGHTS

- Phytoremediation, an eco-friendly method utilizing plants for pollutant removal.
- Cost-effective, reduces the need for extensive infrastructure.
- Challenges include time-consuming processes, site-specific efficacy, and plant species selection.
- Both advantages and challenges are crucial for optimal use in diverse remediation scenarios.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water, a crucial natural resource, sustains life and environments. The two primary categories of natural water resources, surface water and groundwater, play indispensable roles in meeting various human needs. However, the escalating demands resulting from climate change, rapid population growth, overexploitation of natural resources, and accelerated industrialization have imposed immense pressure on freshwater reserves (Calzadilla *et al.* 2011; Connell 2018). The exacerbation of this situation is compounded by industrial activities near water bodies, agricultural runoff, and the release of untreated sewage, collectively contributing to the deterioration of water quality (Azizullah *et al.* 2011; Meghla *et al.* 2013; Weldemariam 2013). Globally, nearly 2 million metric tons of wastewater are dumped into water bodies, particularly affecting poorer nations where surface water bodies receive a significant proportion of untreated industrial effluents and raw sewage (Azizullah *et al.* 2011).

The repercussions of this pollution are severe, with the enrichment of wastewater by heavy metals (HMs) posing threats to human health, plants, and animals (Jeevanantham *et al.* 2019). It is clear from these challenges that wastewater must be treated before being released into an aquatic environment. Wastewater treatment is an essential concern in order to provide clean drinking water and preserve biodiversity. Wastewater treatment aligns with the essential components of the 2030 Sustainable Development Goals (SDGs), contributing to sustainable development by addressing poverty and illness. Traditional wastewater treatment methods, such as distillation systems or using physicochemical techniques like ion exchange, adsorption, reverse osmosis, and UV treatment, have been utilized. However, these techniques often generate sludge and are time-consuming, expensive, and inefficient (Ahila *et al.* 2020; Ali *et al.* 2020).

In recent years, an environmentally friendly technology, phytoremediation, has gained prominence as an alternative for wastewater treatment. Initially explored by Boyd in 1970, phytoremediation employs selected vascular plants to destroy, extract, or isolate pollutants from polluted environments. Subsequent research by Cowgill and others focused on eliminating HMs from wastewater (Outridge & Noller 1991; Ali *et al.* 2013; Rezania *et al.* 2015; Sricoth *et al.* 2018; Ting *et al.* 2018). Some of these techniques are discussed in Figure 1.

Certain plants, termed hyperaccumulators, exhibit the remarkable ability to accumulate substantial quantities of HMs (Andrianisa *et al.* 2008). These plants are suitable for remediation because they can retain HMs in their tissues without experiencing significant damage. Phytoremediation emerges as a viable, economical, and efficient cleanup technique for treating

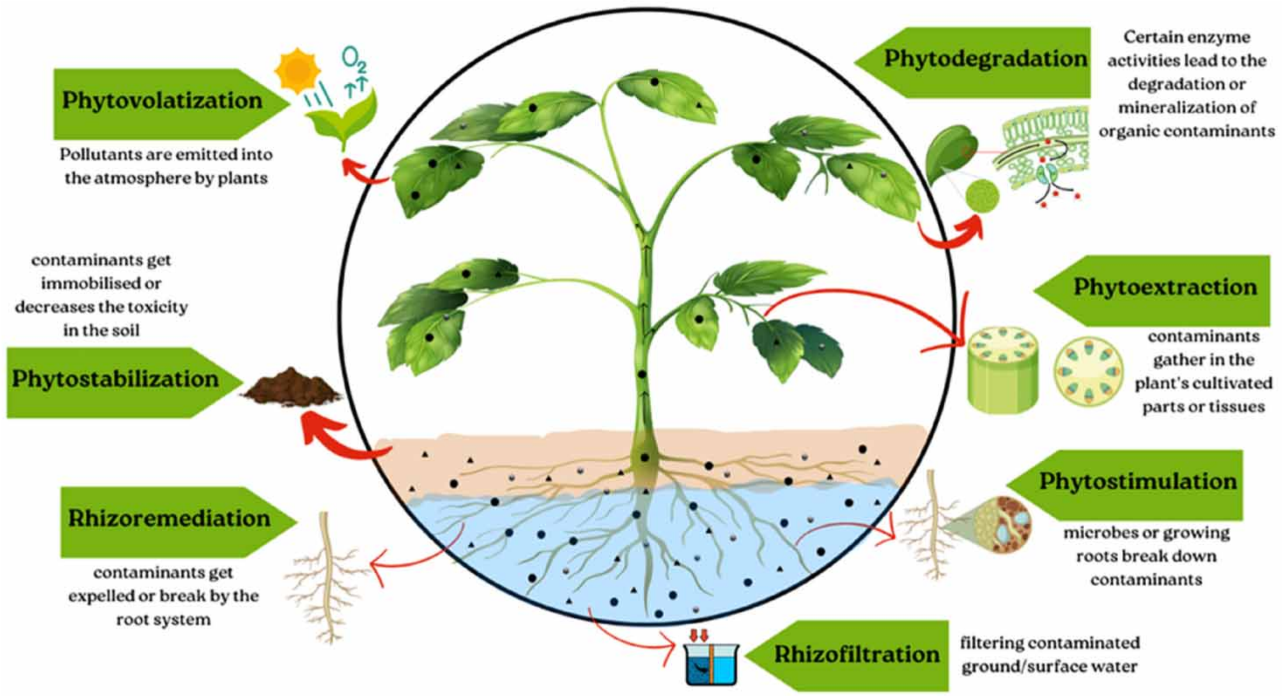


Figure 1 | Different phytoremediation approaches used for wastewater treatment.

groundwater, wastewater, and contaminated soil. Plant species, namely *Eichhornia* sp., *Salvinia* sp., duckweed, *Azollasp.*, *Typha* sp., *Scirpus* sp., *Limnocharisflava*, *Potamogeton* sp., *Myriophyllum* sp., *Spartina* sp., *Cyperus* sp., and *Phragmites* sp., have demonstrated significant potential in eliminating HMs from wastewater (Soda *et al.* 2012; Rodríguez & Brisson 2015).

This study provides a comprehensive analysis of phytoremediation as a sustainable wastewater treatment technique. It delves into the fundamental mechanisms, efficiency, and applications of phytoremediation in various environments. The article proceeds to illustrate the adaptability of phytoremediation through various case studies in diverse environmental contexts, highlighting its potential in addressing the contemporary challenges of water pollution.

2. TYPES OF WASTEWATER CONTAMINANTS

Water bodies face contamination from numerous sources, introducing varied contaminants that impair both environmental and human well-being. The two primary types of pollutants are inorganic pollutants and organic pollutants.

2.1. Organic pollutants

Industries heavily depend on various dyes and chemicals for the synthesis of diverse products, notably cosmetics, medicines, and clothing. Despite their industrial benefits, concerns are mounting over their environmental repercussions, specifically focusing on waterborne organic pollutants characterized by extended half-lives (Baqar *et al.* 2017). Waterborne organic pollutants pose substantial threats to human health, animal populations, and marine life. The spectrum of adverse effects includes severe diseases like learning disabilities, cancer, and birth defects, as well as reproductive, behavioral, and immunological discrepancies in both animals and humans. Organisms along the waterborne food chain, encompassing humans, eagles, polar bears, and killer whales, accumulate these pollutants, resulting in harmful effects and, in some instances, fatalities. Researchers have established connections between waterborne organic pollutants and conditions such as breast cancer, tumor initiation, and elevation in humans. The impact of these pollutants is notably perilous for children, with persistent organic pollutants hindering cell development in this demographic (Tahir *et al.* 2022). Waterborne organic pollutants encompass a range of substances with carbon-based molecular structures. Some of the examples of organic pollutants are represented in Figure 2. Out of these, pesticides and petroleum hydrocarbons will be discussed in subsequent sections.

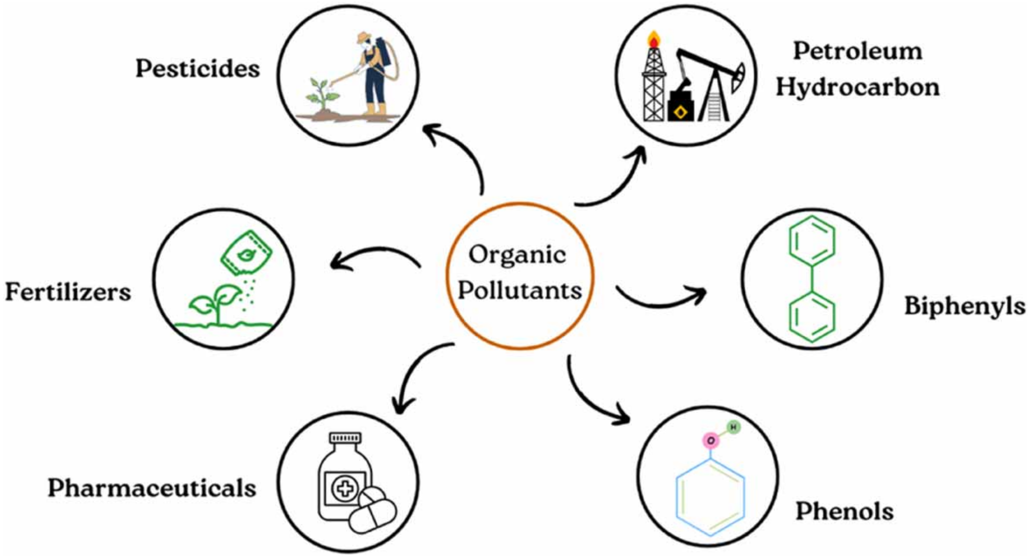


Figure 2 | Various natural and anthropogenic sources of organic pollutants.

Recent reports underscore the global contamination of water sources by a diverse array of organic pollutants, including pharmaceutical waste, dyes, and pesticides, precipitating severe environmental challenges. The unregulated discharge of untreated waterborne organic pollutants into water systems poses harmful effects on living organisms and ecosystems (Madima *et al.* 2020). Carrying carcinogenic potential, toxicity, and mutagenic properties, many waterborne organic pollutants, particularly dyes, exhibit high toxicity even at low concentrations (Yang 2011; Shanker *et al.* 2017). Moreover, the intricate structures of these waterborne contaminants render them extremely impervious to biodegradation and impervious to conservative physical and biological oxidation treatments.

2.1.1. Pesticides

The destiny of pesticides in the environment is intricately linked to their physicochemical properties, particularly their water solubility determined by the octanol–water partition coefficient and their mobility and persistence in the soil. Beyond inherent properties, water pollution from pesticides is influenced by numerous factors, including climatic conditions (precipitation, temperature, wind, and humidity), cultivation practices, hydrogeological characteristics, application speed, soil type (organic matter content and texture), frequency, product amounts, seasonality, and trophic status (Worrall & Kolpin 2004; Carles *et al.* 2019).

Pesticides, classified by target species such as fungicides, insecticides, and herbicides, are extensively used in both urban settings and agricultural farmland (De *et al.* 2014). Fungicides, utilized to prevent fungus infection in seeds or plants, are applied either before the presence of fungus or after infection. Insecticides, employed to control insects, and herbicides, designed to eliminate weeds, are prevalent in farmlands and other areas (Syafrudin *et al.* 2021). Pesticides can also be categorized on the basis of their mode of action, like agents that repel, destroy, or mitigate (Mahmood *et al.* 2016), and through a more scientific approach considering their chemical composition.

These chemicals, partly soluble in water, elicit more concern for their residues in foods than in drinking water. Pesticides that are synthetic and organic, such as DDT, endrin, aldrin, and chlorinated hydrocarbons like chlordane, have a tendency to build up in food chains. Even though they are extremely hazardous, organophosphorus chemicals like malathion and diazinon, which were created as alternatives to chlorinated hydrocarbon pesticides, break down quickly in the environment and lose their presence in groundwater. Since carbamate insecticides have a limited ability to bind to soil particles, they may find their way into surface waters as a substitute for chlorinated hydrocarbons (Riyaz *et al.* 2022).

2.1.2. Petroleum hydrocarbons

Marine petroleum hydrocarbons have two primary sources: natural (diagenetic or biogenic) and anthropogenic (pyrogenic or petrogenic) (Adeniji *et al.* 2017). Diagenetic sources result from transformations in sediment, while biogenic hydrocarbons originate from living organisms. Natural seepage serves as a prevalent route for these hydrocarbons to infiltrate marine water (Kvenvolden & Cooper 2003). Anthropogenic hydrocarbons, more prevalent in the environment, result from several human activities such as urbanization, transportation, industrialization, oil operations, shipping, fishing, and storage (Sakari *et al.* 2008; Strother *et al.* 2013).

Oil industries, particularly during production, refining, transportation, and storage processes, play a substantial role in water pollution through the discharge of oily wastewater (Al-Futaisi *et al.* 2007). Accidental spills, frequently occurring on ships, oil platforms, and during oil transportation, result in hydrocarbon pollution in water. This leads to petroleum products forming a water-resistant film on seawater, hindering oxygen exchange, and causing harm to marine life (Obida *et al.* 2018). The increased use of vehicle oil, a major contributor to petroleum hydrocarbon contamination in water, results in runoff from oil drops onto the ground, eventually washing into water streams (Mfarrej *et al.* 2023).

2.2. Inorganic pollutants

The formidable presence of inorganic pollutants, specifically HM ions, constitutes a severe threat to organisms, influenced by both anthropogenic and geological factors (Tarannum & Khan 2020). The escalation of harmful pollutants in water results directly from the increasing social, agricultural, industrial, and domestic activities. There are several ways that inorganic contaminants enter natural ecosystems. Non-point contributors, including agriculture plant wastewater, and point sources like treatment centers located across the city, pharmaceutical, cosmetics, and sanitary industries contribute to contamination. Groundwater pollution is influenced by interactions involving leaching from agricultural fields, rivers, and sewage networks (Ebele *et al.* 2017).

Inorganic pollutants encompass industrial waste, nutrients, HM, and sediments (Zhang *et al.* 2020), out of which HM and nutrients are discussed in a subsequent section. Although many of these pollutants exist naturally, human activities like agriculture, mining, and industrial processes have escalated their amounts in the environment (Madima *et al.* 2020). Most inorganic pollutants are not biodegradable, and when they build up in the body, they can cause serious health problems (Lu & Astruc 2018). The global prevalence of inorganic pollutants, especially HM such as zinc (Zn), lead (Pb), iron (Fe), cadmium (Cd), chromium (Cr), arsenic (As), cobalt (Co), and nickel (Ni), represents an urgent environmental concern affecting both developing and developed nations (Baruah *et al.* 2016; Bashir *et al.* 2019; Malik *et al.* 2019). These carcinogenic, non-biodegradable, and highly toxic metals necessitate prompt removal from water before release into the environment (Malik *et al.* 2017; Talaiekhozani & Rezania 2017; Abdi *et al.* 2018).

2.2.1. Heavy metals

The HM contamination is often linked to industrial wastewater; it is noteworthy that in developing regions, these contaminants extend to various water sources such as lakes (Archundia *et al.* 2017; Xu *et al.* 2017), domestic wastewater seepage (El Khatib *et al.* 2012), rivers (Mwanamoki *et al.* 2015), and groundwater (Kumarasinghe *et al.* 2017; Sridhar *et al.* 2017). The introduction of these metals into the environment results from improper waste discarding, diverse agricultural practices, and industrial activities (Chowdhury *et al.* 2016). Essential for the growth of living organisms, HM like copper (Cu), Zn, Cr, and Fe become challenging due to their tenacious nature, leading to bioaccumulation in humans and animals through contaminated water consumption (Joseph *et al.* 2019). Figure 3 illustrates the harmful effects of various HMs on diverse parts of the human body.

Categorized among the most perilous substances due to their deadly nature (Järup 2003), HM infiltrates water from several industrial sources, including mining, metal plating, painting, tanneries, fertilizers, and batteries (Javadian 2014; Mahmud *et al.* 2016). Whether directly or indirectly, metals like Co, As, mercury (Hg), Pb, Cu, Cd, Zn, Ni, and Cr enter water bodies and persist in various oxidation states for extended periods (Yadav *et al.* 2019). Urban pollution contributes HM through polluted air, dust, and sediment, with these contaminants traveling over long distances in both non-biological and biological forms. The biological form is particularly significant, posing heightened risks to humans and ecosystems. Therefore, the imperative remains for the elimination of HM ions from contaminated wastewater before discharge into water bodies (Yadav *et al.* 2019).

2.2.2. Nutrients (phosphorus and nitrogen)

The excessive loading of nutrients, particularly nitrogen (N) and phosphorus (P), stands as a critical ecological concern and a prominent water quality issue in contemporary surface water bodies (Badruzzaman *et al.* 2012). While these nutrients are vital for the persistence of aquatic organisms, their excessive loading can have adverse effects on the designated usage of

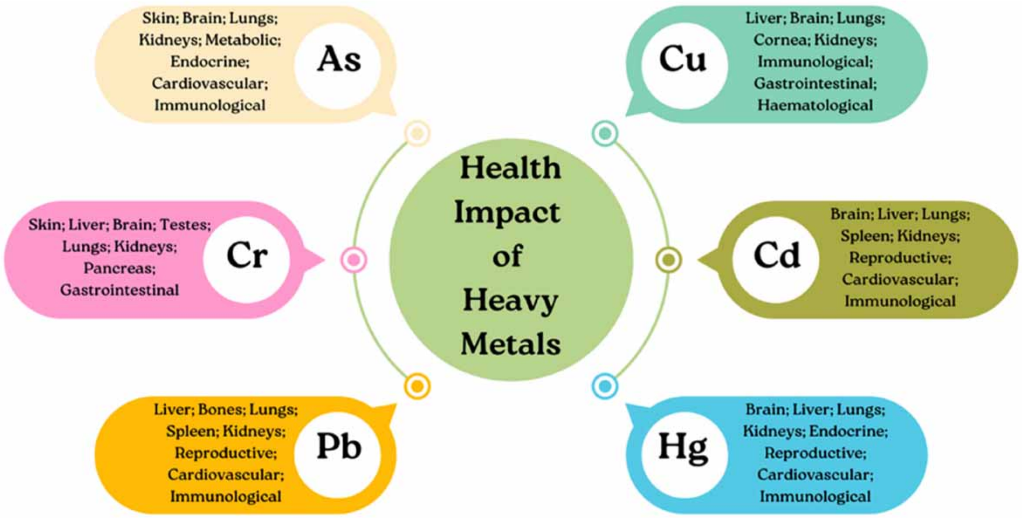


Figure 3 | Impact of HMs on human body.

water (Freeman *et al.* 2009). Nutrient enrichment in water bodies results from a combination of natural and anthropogenic sources, with several factors influencing the loading process, including bioavailability, source output, loading mode, location, seasonal variation, specification, and concentration (Withers & Jarvie 2008).

The primary catalyst for the increased loading of nutrients into water resources is linked to the production of agricultural food (Han & Allan 2012). Multiple sources contribute to the excess nutrient loading in water bodies, including potential influence from climate change, inappropriate land usage and management, and intensive and poor farming practices (Wang *et al.* 2010; Castillo *et al.* 2014; Giri *et al.* 2014). Significantly, the primary sources of N and P pollution in water bodies are the result of sewage effluents originating from detergents and human waste and excess agricultural nutrients (Bayram *et al.* 2013).

By understanding and harnessing the capabilities of plants, phytoremediation emerges as a promising approach to mitigate the diverse range of contaminants threatening water ecosystems. A profound understanding of the intricate interactions between these contaminants and water ecosystems is essential for formulating effective remediation strategies. Phytoremediation, grounded in plant-mediated processes, emerges as a promising and sustainable approach to water purification. The upcoming section delves into how plants actively engage in improving water pollution, emphasizing a nature-centric strategy that holds considerable promise for transforming environmental remediation methodologies.

3. PHYTOREMEDIATION MECHANISMS

Phytoremediation, an eco-friendly remediation approach, depends on diverse mechanisms utilized by plants to alleviate the impact of contaminants in wastewater. A profound comprehension of these mechanisms is essential for enhancing the efficiency of phytoremediation strategies. Figure 4 intricately displays the fundamental mechanisms involved in the process.

3.1. Uptake and accumulation

The initiation of phytoremediation involves the absorption of pollutants by plant roots, functioning as natural filters that selectively draw pollutants from the surrounding water (Abdel-Shafy & Mansour 2018). This process engages physiological mechanisms facilitating the transport of contaminants from water into plant tissues. A thorough examination of factors influencing uptake efficiency becomes crucial for judiciously selecting plant species across phytoremediation applications (Kvesitadze *et al.* 2015).

3.2. Transformation and detoxification

Subsequent to the absorption of contaminants, plants undergo biochemical processes for the transformation and detoxification of pollutants (Singh & Jain 2003). This involves metabolic activities within plant cells, leading to the conversion of toxic substances into less harmful forms. A thorough investigation into the enzymatic pathways governing this transformation provides insights into the potential of different plant species to detoxify specific contaminants (Jabeen *et al.* 2009).

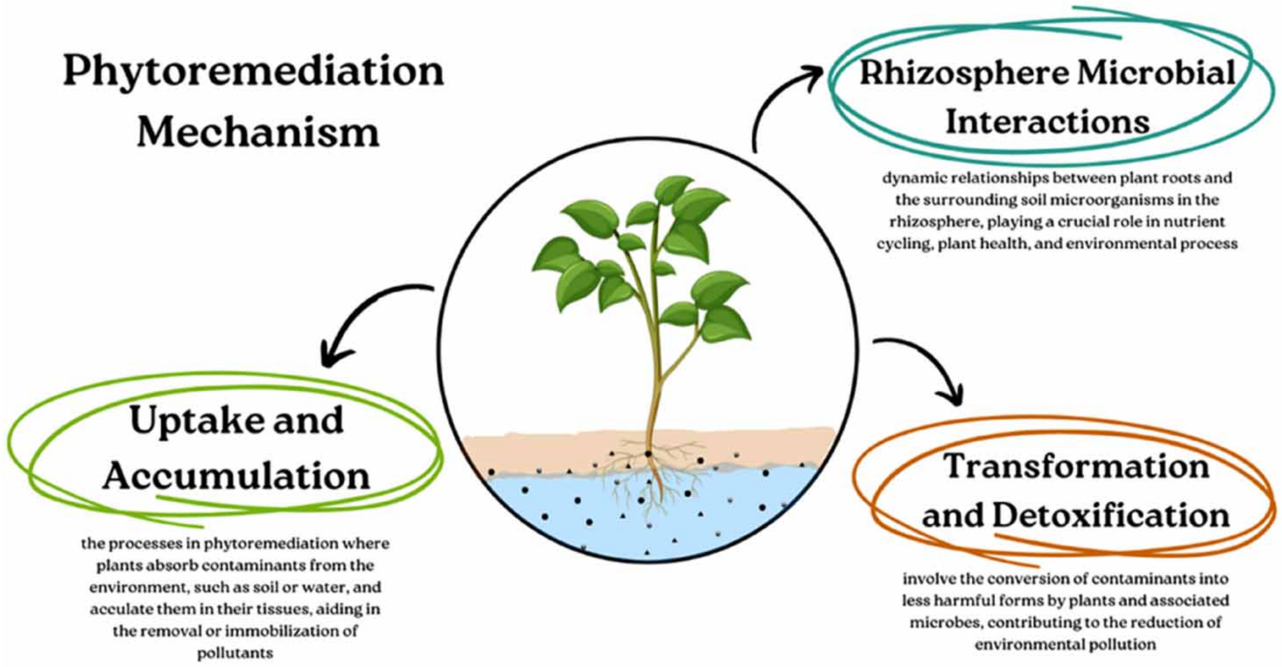


Figure 4 | A flowchart of the mechanisms involved in phytoremediation.

3.3. Rhizosphere microbial interactions

The rhizosphere, influenced by root secretions, plays a pivotal role in the phytoremediation process. Microorganisms within this zone actively contribute to contaminant degradation and nutrient cycling. A detailed exploration of interactions between plant roots and rhizospheric microbes offers valuable insights into microbial-assisted mechanisms that enhance the overall efficiency of phytoremediation (Agarwal *et al.* 2020).

Understanding these fundamental phytoremediation mechanisms is vital for the development of sustainable and effective wastewater treatment strategies. Subsequent sections will explore specific phytoremediation types and explore case studies demonstrating the application of these mechanisms in diverse environmental contexts.

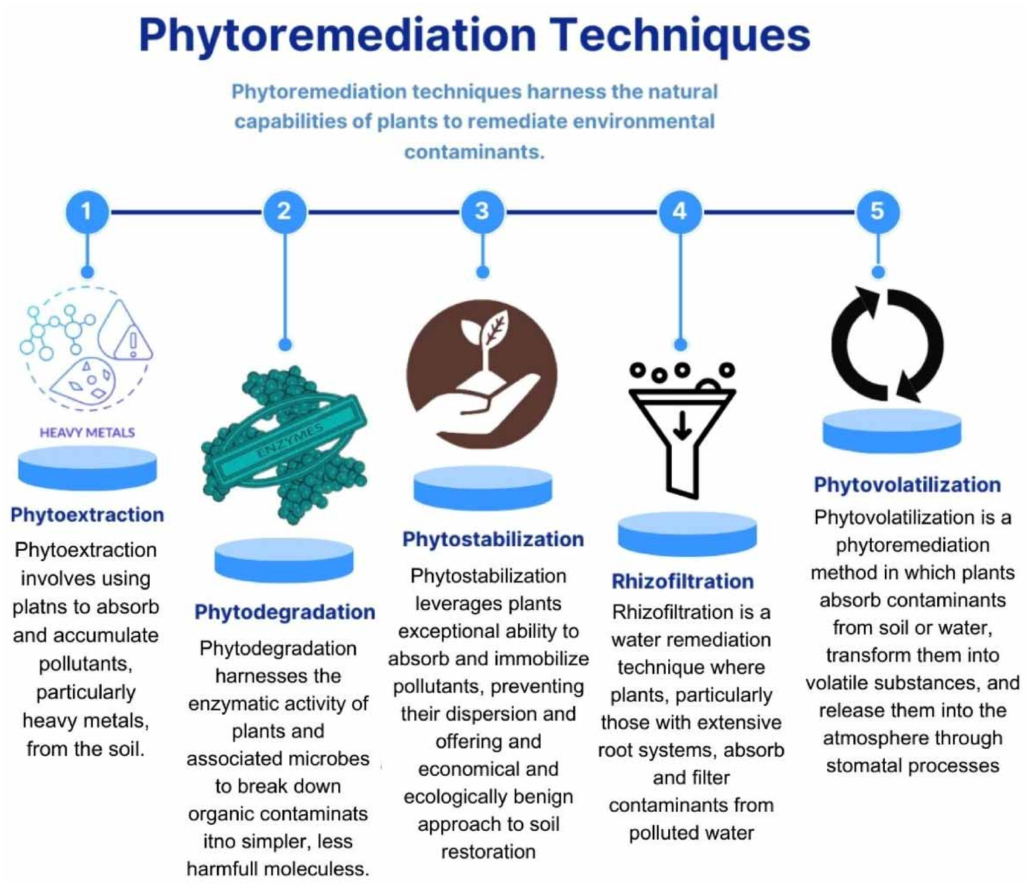
4. TYPES OF PHYTOREMEDIATION

Phytoremediation, an innovative plant-based method for *in-situ* elimination of HMs from contaminated environments, has gained global attention (Liu *et al.* 2020; Yang *et al.* 2020). As an application of plant sciences, phytoremediation seeks to harness the natural capabilities of plants to improve living conditions for humans. This approach utilizes the symbiotic relationship between rhizosphere organisms and plant physiology to eliminate persistent or hazardous contaminants from soils and waterways, particularly in regions with limited waterway pollution treatment (Schwitzguébel *et al.* 2011).

The versatility of phytoremediation extends its applicability to various purposes, including wastewater treatment, purification of surface and groundwater, recovery of soil affected by natural disasters, and the elimination of excessive nutrients from water basins (Dordio & Carvalho 2013). Notably, this technique comprises five approaches – phytoextraction, phytodegradation, phytostabilization, rhizofiltration, and phytovolatilization (Figure 5) – which will be discussed in subsequent sections. The use of plant-based remediation techniques not only addresses environmental pollution but also contributes to sustainable and eco-friendly solutions for managing diverse forms of contaminants in different environments.

4.1. Phytoextraction

Phytoextraction, a technique involving the cultivation of plants in polluted areas with the ability to accumulate HMs, facilitates the harvesting of metal-enriched biomass upon maturity (Pajević *et al.* 2016). This method aids in removing contaminants from the soil. The efficacy of phytoextraction as an environmentally friendly approach depends on the ability of plants to absorb and store metals in their aerial parts, considering metal availability for absorption. Typically, the collected



Phytoremediation Techniques

Phytoremediation techniques harness the natural capabilities of plants to remediate environmental contaminants.

Phytoextraction

Phytoextraction involves using platns to absorb and accumulate pollutants, particularly heavy metals, from the soil.

Phytodegradation

Phytodegradation harnesses the enzymatic activity of plants and associated microbes to break down organic contaminats itno simpler, less harmfull moleculess.

Phytostabilization

Phytostabilization leverages plants exceptional ability to absorb and immobilize pollutants, preventing their dispersion and offering and economical and ecologically benign approach to soil restoration

Rhizofiltration

Rhizofiltration is a water remediation technique where plants, particularly those with extensive root systems, absorb and filter contaminants from polluted water

Phytovolatilization

Phytovolatilization is a phytoremediation method in which plants absorb contaminants from soil or water, transform them into volatile substances, and release them into the atmosphere through stomatal processes

Figure 5 | Illustration of several phytoremediation approaches used to harness the natural abilities of plants for environmental remediation.

biomass is either composted or incinerated, with limited recycling for further use (Prasad & De Oliveira Freitas 2003; Bhargava *et al.* 2012). Several essential plant characteristics contribute to successful phytoextraction, including the ability to cover a broad area, rapid growth, substantial biomass production, flexibility in harvesting, and the capacity to accumulate various HMs in their harvestable sections (Jabeen *et al.* 2009; Seth 2012).

Phytoextraction processes are generally categorized as induced or continuous. Continuous phytoextraction involves using plants that accumulate toxins throughout their entire life cycle, while induced phytoextraction employs chelators to increase toxin growth at specific stages of plant development (Starck 2005; Mukhopadhyay & Maiti 2010; Materac *et al.* 2015). Table 1 provides insights into various researchers utilizing phytoextraction technology for toxin removal, employing diverse plant species and methodologies.

The effectiveness of phytoextraction is determined by the plant's growth rate, biomass production, and root depth. *Alyssum* species, for example, have been demonstrated to efficiently reduce the amounts of soil metals (Dehghani *et al.* 2021). It is efficient; up to a 60–70% reduction in soil metal concentrations which can be achieved by hyperaccumulator plants such as *Alyssum*. A high output of biomass is essential; certain species, such as Indian mustard (*Brassica juncea*), may generate 20–30 tons of biomass yearly per hectare (Farooq & Khanday 2020). Depending on pollution levels, the process can take multiple growing seasons to accomplish considerable metal reduction; this can take up to five years. Phytoextraction can be used on a wide scale, particularly in agricultural and industrial areas where there is lot of soil pollution (DalCorso *et al.* 2019; Bhat *et al.* 2022).

Phytoextraction is a widely recommended green remediation approach, however it still has a lot of practical limits and needs further study. It takes a lot of time and administrative work, which prevents it from being quickly installed in hotspots with high levels of contamination. The ability of HMs to accumulate is hampered by insect attacks and diseases they cause. The efficiency of phytoextraction is influenced by various environmental factors, including pollutant distribution

Table 1 | Research studies on phytoextraction and phytodegradation techniques

Type of Wastewater	Plant species used	Pollutants	Outcomes	Reference
Phytoextraction Technique				
Artificial wastewater	Wetland plant species	Cu, Cr, and Ni	More than 97% of pollutants such as Cu (8.8%), Cr (20.5%), and Ni (14.4%) were removed from the wastewater.	Liu *et al.* (2010)
Synthetic wastewater	*Arundo donax*	As	*A. donax* plants can treat polluted waters containing As concentrations up to 600 μg L^{-1}.	Mirza *et al.* (2010)
Aqueous solution	*Potamogeton pusillus*	Cu, Cr	*P. pusillus* is capable of accumulating a significant amount of Cu and Cr from individual solutions (either Cu^{2+} or Cr^{+6}).	Monferrán *et al.* (2012)
Biosolids – end product of wastewater treatment process	Willows (*Salix* × *reichardtii* A. Kerner)	Cd, Zn, Ni, Cu	Flood-irrigation with reclaimed water to grow willows in a dry climate. The reclaimed water can also change biosolids properties, which will influence the effectiveness of willows to extract different metals.	Laidlaw *et al.* (2015)
Simulated polluted river water	*Iris sibirica*	Cd	The average removal rate of Cd from the wastewater could reach 91.8%. Wastewater polluted by Cd could be treated effectively using microcosmic subsurface vertical flow-constructed wetlands with the *I. sibirica* plant.	Gao *et al.* (2015)
Wastewater	*Tradescantia pallida*	Cr (VI)	Maximum Cr(VI) removal efficiency was 97.2–98.3%, and maximum total Cr removal efficiency was 86–88.2%.	Sinha *et al.* (2017)
Municipal sewage sludge	Jatar (*Rosa multiflora* Thunb. ex Murray) and Virginia fanpetals (*Sida hermaphrodita* Rusby)	HMs (Cr, Ni, Cu, Zn, Cd, Pb)	Virginia fanpetals were more efficient in the phytoextraction of Cr, Ni, Cu, Zn, and Cd from the sewage sludge than the multiflora rose. Multiflora rose phytoextracted greater amounts of Pb from the sewage sludge.	Antonkiewicz*et al.* (2017)
Wastewater	*Limnobium laevigatum*	Cr, Zn, Pb, Ni	The accumulation of Pb, Cr, Ni, and Zn in roots was higher than in leaves of *L. laevigatum*. This species can be considered a hyperaccumulator of Ni and Zn.	Arán *et al.* (2017)
Sewage effluent irrigated sandy soil	Sorghum (*Sorghum bicolor*)	Aluminium (Al), Zn, manganese (Mn), Cd, Ni, Cu, Fe, Cr	Soil amendments caused contradictory effects on the elements phytoavailability. All amendments increased phytoextraction of Cd, Cu, and Ni compared to control. Sulfur, triple superphosphate, and phosphoric acid immobilized Al, Cr, and Fe. Sugar beet factory lime decreased phytoextraction of Al, Fe, Mn, and Zn. Drinking water treatment residual increased phytoextraction of Al, Cr, and Fe.	Shaheen *et al.* (2017)
Wastewater	*P. trichocarpa* × *P. deltoides*	Boron (B)	High B aqueous concentrations lead to high B accumulation in plant tissue and negatively impact plant biomass. Clone 195–529 had the highest B accumulation and tolerance. Varying salinity levels range from beneficial	Chen *et al.* (2017a)

(*Continued.*)

Table 1 | Continued

Type of Wastewater	Plant species used	Pollutants	Outcomes	Reference
			to harmful for poplar growth and B removal.	
Wastewater	*Tradescantia pallida*	Cr (VI)	Best results achieved for an influent pH of 7 with a maximum Cr(VI) removal efficiency of 97.2–98.3% and a maximum total Cr removal efficiency of 86–88.2%. Excellent Cr uptake potential of *T. pallida*.	Sinha *et al.* (2017)
Untreated industrial/ municipal effluent	Swollen duckweed (*Lemna gibba* Linn.) and lesser duckweed (*Lemna aequinoctialis* Welw.)	Ni, Pb, and Cd	Final metal removal percentages: Ni (97%) > Pb (94%) > Cd (90%) when treated with *Lemna gibba* L. Lesser duckweed did not survive under experimental conditions. *Lemna gibba* L. is a good candidate for phytoremediation of wastewater.	Bokhari *et al.* (2019)
Mine wastewater	Klara (*Salix viminalis* × *S. schwerinii* × *S. dasyclados*)	Cu, Ni, Zn	Lime and N10O stimulate plant growth and phytoextraction efficiency. Klara shows considerable potential to uptake Cu, Zn, and Ni.	Salam *et al.* (2019)
Industrial wastewater	Dhab (*Desmostachya bipinnata*), Sporobolus (*Sporobolus arabicus*), Kallar (*Leptochloa fusca*), and Para grass (*Brachiaria mutica*)	Pb, Cd	Root Pb concentration was highest in B. mutica, followed by D. bipinnata and L. fusca, whereas S. arabicus showed depressed growth, minimum shoot metal accumulation, and uptake potential. B. mutica could be the suitable option to remediate industrial wastewater.	Ullah *et al.* (2020)
Distillery wastewater	*Ricinus communis* L.	Cr, Fe, Cu, Pb, Zn, Ni, Mn	*Ricinus communis* L. shows phytoremediation potential of metals. Reduction of BOD, COD, and metals is >70% using *Ricinus communis* L.	Tripathi *et al.* (2021)
Wastewater	Vetiver grass (*Chrysopogon zizanioides*)	Cr (VI)	Reduction in Cr(VI) concentration : 5 ppm (87%), 10 ppm (51%), 30 ppm (28%), and 70 ppm (12%). Potential of vetiver grass in phytoextraction of Cr(VI) and its hyperaccumulator potential for other HMs.	Masinire *et al.* (2020)
Industrial wastewater	*Scirpus grossus.*	Pb	Pb removal in water: efficiency (99.9%), error (0.2%), absorption by plants (5,160.18 mg/kg with 10.6% error). HFSFCW under optimum conditions with no bioaugmentation might be a feasible choice for the treatment of Pb-contaminated water.	Tangahu *et al.* (2022)
Municipal and industrial wastewater	*Typha latifolia* L.	Cd, Cr, Cu, Pb, and Zn	*Typha latifolia* L. was shown to have acceptable performance.	Haghnazar *et al.* (2021)
Textile wastewater	*Lemna minor* L. and *Typha latifolia* L.	Pb, Cr, and Cu	*T. latifolia* and *L. minor* showed higher efficacy for textile effluent treatment under citric acid.	Ishaq *et al.* (2021)
Textile and tannery wastewater	Duckweed (*Lemna minor* L.)	Cd, Cr, Pb, Cu, and Ni	HMs concentration increased under acetic acid up to: Cr (116 & 422%); Cd (106 & 416%); Pb (72 & 351%); Cu (76 & 346%); and Ni (41 & 328%).	Farid *et al.* (2022)

(*Continued.*)

Table 1 | Continued

Type of Wastewater	Plant species used	Pollutants	Outcomes	Reference
Phytodegradation Technique				
Agro-industrial wastewater	Water hyacinth (*Eichhornia crassipes*)	P pesticide ethion	Accumulated ethion in water hyacinth plants decreased in: shoots (55–91%) and roots (74–81%).	Xia & Ma (2006)
Aqueous solution	*Azolla filiculoides*	Bisphenol A (BPA)	BPA removal: 60–90% Removal efficiency: more than 90% (BPA concentration = 5 ppm & amount of biomass = 0.9 gr).	Zazouli *et al.* (2014)
Municipal wastewater treatment plants	Wetland (*Cyperus alternifolius* L.)	Oxybenzone (OBZ)	Higher accumulation of OBZ occurs in roots rather than in shoots.	Chen *et al.* (2017b)
Urban wastewater	*T. angustifolia* L.	1,2-Dichloroethane (1,2-DCA)	1,2-DCA removal: 100% (after 95 days) Removal efficiency: 18% (with addition of compost).	Al-Baldawi (2018)
Industrial wastewater	Duckweed (*Spirodela polyrhiza*)	Amoxicillin	Amoxicillin reduction: 84.6–100%.	Singh *et al.* (2018)
Industrial wastewater	Duckweed (*Spirodela polyrhiza*)	Ofloxacin (OFX)	OFX reduction: 93.73–98.36%.	Singh *et al.* (2019)
Industrial wastewater	*Canna indica*	Atenolol (ATL), diclofenac (DCF), carbamazepine (CBZ)	Microbial degradation: 80–93%.	Ravichandran & Philip (2022)

irregularities, soil pH, temperature variations, and moisture content (Prasad *et al.* 2022). Large-scale soil disposal raises environmental concerns even when the cleanup is completed quickly and all pollutants are eliminated (Robinson *et al.* 2015). Another significant challenge linked to the phytoextraction approach is the potential for food chain contamination due to the direct introduction of accumulated metals from plant biomass into the environment, if not managed appropriately (Mahar *et al.* 2016). Addressing these issues requires continued research and development to optimize phytoextraction methods and ensure safe and effective remediation.

Recent technological advancements in the last several years have brought new, creative, and effective ways to maximize the potential of phytoextraction. Genetic engineering and selective breeding can introduce or overexpress genes for metal tolerance, translocation, hyperacuumulation, and detoxification in plants with rapid growth and high biomass production (Prasad *et al.* 2022). As a result, phytoextraction's practical usefulness is much improved. There have been encouraging findings about HM accumulation in a number of genetically modified plants. For example, owing to the overexpression of the γ-glutamylcysteine synthetase enzyme, *Silene cucbalus*, *Populas angustifolia*, and *Nicotiana tabacum* have shown excessive accumulation of HMs (Fulekar *et al.* 2009). It has also been observed that overexpressing Saccharomyces cerevisiae's YCF1 vacuolar transporter increases the absorption of complexes containing As, Cd, and Hg. According to Yadav *et al.* (2010), transgenically modified *Arabidopsis thaliana* exhibited a four-fold increase in Cd absorption when compared to wild-type plants. These advancements show how genetic alterations may greatly increase the efficacy and efficiency of phytoextraction, making it a more practical choice for extensive environmental rehabilitation.

4.2. Phytodegradation

Phytodegradation involves harnessing the enzymatic activity of plants and their associated microbes to convert organic contaminants into simpler molecules (Lakshmi *et al.* 2017). This process relies on plants' capacity to produce necessary enzymes that initiate the breakdown of xenobiotics (Alkio *et al.* 2005). The accomplishment of phytodegradation hinges on collaborative interactions among soil, water, microbes, and plants, with the plant's role being pivotal in providing a surface area for bacteria colonization around the shoot and root. This, in turn, enhances microbial activity, facilitating the breakdown of carbon substrates (Lakshmi *et al.* 2017).

Researchers suggest that phytodegradation is applicable in various habitats, encompassing surface and groundwater, soil, as well as river sediments and sludges (Edwards & Dixon 2004; Malecka & Tomaszewska 2005; Materac *et al.* 2015). Table 1 succinctly presents key findings from several studies, highlighting the adaptability and efficiency of phytodegradation in addressing challenges posed by organic pollution in diverse environmental contexts. The versatility of phytodegradation as a method for breaking down organic contaminants underscores its potential in addressing environmental pollution concerns across different scenarios.

Plants with broad root systems and quick growth, such as poplar (*Populus* spp.) and willow (*Salix* spp.), are frequently employed. For some organic pollutants, such as polycyclic aromatic hydrocarbons, phytodegradation can reach a degradation efficiency of up to 90% (Alagić *et al.* 2015). Large regions of soil and water polluted by organic pollutants, such as industrial waste sites and agricultural runoff areas, respond well to this treatment approach. Although phytodegradation is a promising method for treating wastewater, there are a number of limitations that prevent its widespread use. The heterogeneity in plant species' capacities to absorb and decompose certain pollutants is a significant problem that can lead to uneven treatment results. Climate variables like pH, temperature, and the availability of nutrients have a big influence on how well phytodegradation works (Qadir *et al.* 2020; Ullah *et al.* 2023). Depending on the pollution and the surrounding circumstances, the process might take months or years, and it is comparatively slow. When severe or mixed metal contamination occurs, its applicability is more constrained (He *et al.* 2022).

The efficacy and applicability of this green remediation strategy have been greatly increased by developments in phytodegradation methods. Among the most recent developments is the use of genetically engineered plants that express enzymes that more efficiently degrade a variety of organic contaminants (Rai *et al.* 2020). For example, plants are able to break down complex organic pollutants like pesticides, medicines, and industrial chemicals since genes encoding for enzymes like laccases, peroxidases, and cytochrome P450 monooxygenases have been inserted into the plants (Takkar *et al.* 2022). Further research has demonstrated that the creation of symbiotic plant–microbe systems in which some microorganisms aid in the process of degradation can accelerate the rate at which pollutants decompose (Padhan *et al.* 2021). These developments in biotechnology, along with the improvement of growing conditions and plant species selection, have strengthened and increased the viability of phytodegradation as a wastewater treatment and pollution mitigation technique.

4.3. Phytostabilization

Phytostabilization relies on plants' exceptional ability to absorb and store pollutants, leading to their immobilization or solidification (Chandekar & Godboley 2015). This approach effectively hinders the dispersion of pollutants through precipitation runoff, inhibiting their entry into groundwater and migration to surface soil. Plants selected for phytostabilization exhibit desirable characteristics, such as a robust root system that promotes the adsorption and accumulation of pollutants in tissues. The absorption of pollutants and their conversion into less soluble composites in the rhizosphere further enhances the efficacy of phytostabilization (Segura & Ramos 2013; Materac *et al.* 2015).

By employing plants to stabilize pollutants and impede their movement via wind or water, phytostabilization aims to reduce the bioavailability of toxins (Lakshmi *et al.* 2017). This method becomes particularly valuable when an extended phytoextraction process is impractical, making phytostabilization an economical and ecologically benign restoration technique. It proves especially suitable for soils with high metal content and widespread pollution (Wong 2003; Alkorta *et al.* 2010; Dary *et al.* 2010).

Researchers have implemented phytostabilization techniques to address various types of pollutants in wastewater. Table 2 offers an overview of some of these studies, emphasizing the adaptability and efficacy of phytostabilization in dealing with contamination issues. These methods stand out as a valuable tool in the arsenal of phytoremediation strategies, providing sustainable solutions for environmental restoration in the face of diverse pollution challenges.

Plants with extensive root systems, such as legumes and grasses, are frequently utilized because they aid in immobilizing contaminants. By using this technique, HM bioavailability can be decreased by up to 80% (Ogundola *et al.* 2022). Plants with large root biomass, like vetiver grass, are very productive and may produce ten to fifteen tons of root mass per hectare. Large-scale land reclamation operations are most suited for phytostabilization, particularly in mining and waste sites where controlling the spread of pollutants is essential (Gnansounou *et al.* 2017; Bakshe & Jugade 2023). Although a promising method for treating wastewater, phytostabilization has a number of important drawbacks. It works less well in places

Table 2 | Research studies on phytostabilization and rhizofiltration techniques

Type of wastewater	Plant species used	Pollutant	Outcomes	References
Phytostabilization Technique				
Mining wastewater	Wetland plants (*Phragmites mauritianus* and *Typha* spp.)	Co, Cu, Pb	*P. mauritianus* and *Typha* spp. provide the potential for phytostabilization.	Nabuyanda *et al.* (2022)
Land-derived wastewater	*Avicennia marina*	Pb, Cu, and Zn	*A. marina* has shown the ability compartmentalization of HMs.	Nath *et al.* (2014)
Canal wastewater	*Vossia cuspidate (Roxb.)* and *Griff.*	Cr, Pb, Cu, Al, Zn, and Cd,	Spring plants accumulated the highest concentrations in: root (Cr, Cu, Pb); and lowest in: shoot (Al, Cd, Cr, Zn).	Galal *et al.* (2017)
Lake water	*Ranunculus sceleratus*	Mn, Ni, Zn, Cd, Cu, Pb	Bioaccumulation factor (BF): 27.1 (Ni) > 20.0 (Zn) > 16.4 (Cd) > 7.7 (Cu) > 3.9 (Mn) > 3.6 (Pb).	Farahat & Galal (2018)
Industrial wastewater	*Petunia hydrida* L. and *Nicotiana alata* L.	Ni, Cd, Pb, Cu, Cr, Mn, and Zn	Both are suitable for treatment of HMs in wastewater.	Khan *et al.* (2019)
Mining wastewater	*S. grossus*	Fe and Al	Boosts the phytostabilization of Al and Fe.	Ismail *et al.* (2020)
Wastewater	*Salix* species (*Salix myrsinifolia* and *Salix schwerinii*)	Lanthanum (La)	*Salix* could be a suitable candidate to accumulate rare earth elements.	Mohsin *et al.* (2022)
Swine wastewater	*Eucalyptus grandis*	Cu	It can be used for phytostabilization.	Negrini *et al.* (2022)
Sewage wastewater	Wetland plants (*Typha latifolia* and *Phragmites australis*)	Cu, Cd, Pb, Cr, Zn, and As	Both are suitable for phytostabilization.	Xiong *et al.* (2024)
Stormwater	*Phragmites australis* and *Iris pseudacorus*	Cd	Both have accumulated the highest Cd in roots than shoots. Appropriate for removing Cd polluted sites.	Mohsin *et al.* (2023)
Rhizofiltration Technique				
Industrial wastewater	Water hyacinth (*Eichhornia crassipes* (Mart.) Solms)	Fe	Water hyacinth grown under poor-nutrient conditions is ideal to remove Fe.	Jayaweera *et al.* (2008)
Groundwater	Bean (*Phaseolus vulgaris* L.) and Sunflower (*Helianthus annuus* L.)	U	Removal efficiency for: sunflower (80%); bean (60–80%). U removal via rhizofiltration exceeded 90%.	Lee & Yang (2010)
Contaminated nutrient solution	Lettuce (*Pistia stratiotes* L.)	Cd and Pb	Pb treatment: transpiration rate decreases. Cd treatment: transpiration rate increases.	Veselý *et al.* (2011)
Aqueous environment	*Azolla pinnata*	Pb (II)	Efficiency of Pb removal depends on exposure duration. Max. uptake of Pb : 1,383 mg Kg^{-1} Reduction in Pb conc.: 83%.	Thayaparan & Iqbal (2013)
Eutrophic water	*Pistia stratiotes*	Pb, Cr, and Ni	Uptake of Ni is higher than others.	Abubakar *et al.* (2014)
Wastewater	*Phragmites australis*	As		

(*Continued.*)

Table 2 | Continued

Type of wastewater	Plant species used	Pollutant	Outcomes	References
			Effective way to enhance rhizofiltration.	Pardo *et al.* (2016)
Domestic wastewater	*Pistia stratiotes*	Chemical oxygen demand (COD)	Max. absolute growth rate: 13.51–16.54 g_{dw}/day. Avg. biomass productivity: 5.808 g_{dw}/m^2 days.	(Olguín *et al.* (2017)
Industrial wastewater	Pea (Pisum *Sativum* L.)	Tetracycline	Cost-effective strategy Wastewater can be reused for irrigation.	Yagoubi *et al.* (2023)
Dairy wastewater	*Coleus scutellarioides* and *Portulaca oleracea*	Total suspended solids (TSS), total dissolved solids (TDS), biochemical oxygen demand (BOD), COD, total phosphorus (TP), phosphate (PO_4^{3-}), and total nitrogen (TN)	Reduction: 79.43% (TSS); 64.36% (TDS); 82.36% (BOD); 81.86% (COD); 75.55% (TP) (Das & Paul 2023) 74.67% (TN).	Das & Paul (2023)
Domestic wastewater	*Scirpus grossus*	Ibuprofen and paracetamol	Removal efficiency: 45% (Ibuprofen); 31% (Paracetamol).	Falahi *et al.* (2022)

where quick contamination removal is necessary. Choosing suitable plant species that can tolerate elevated pollution levels and diverse environmental circumstances is crucial to the effectiveness of this technique (Shen *et al.* 2022). The effectiveness of phytostabilization can be significantly impacted by soil parameters like pH, moisture content, and nutrient availability. There is also an environmental concern regarding the possibility of contaminant leakage or transport to non-target locations (Lacalle *et al.* 2023). The practical use of phytostabilization for wastewater treatment is made more difficult by the gradual stability of pollutants and the possibility of bioaccumulation in plant tissues.

In order to improve the immobilization of pollutants in soil and sediments, recent developments in phytostabilization approaches for wastewater treatment have concentrated on the employment of specific plants and biotechnological interventions. Scientists have discovered and employed hyperaccumulator plants, which are exceptionally effective in ensnaring HMs and other contaminants in their root zones. This prevents the pollutants from migrating into groundwater and lowers their bioavailability. It has also been demonstrated that the combination of rhizosphere engineering and mycorrhizal fungus enhances plant growth and pollutant stabilization capacities (Singh *et al.* 2022; Khan *et al.* 2023). Plants with improved resistance to hazardous conditions and higher phytostabilization effectiveness have also been developed via the use of genetic engineering techniques. These developments increase the efficiency of phytostabilization in the long term for treating polluted wastewater.

4.4. Rhizofiltration

Rhizofiltration proves to be a valuable technique for tackling surface wastewater resulting from industrial and agricultural activities, with plants playing a critical role in the remediation process. In this method, plants are either exposed to wastewater soaked in their roots or submerged in purified water. The success of rhizofiltration hinges on selecting plants resistant to low oxygen concentrations, processing a large and rapidly developing root system, yielding substantial biomass, and demonstrating high tolerance to toxic compounds (Srivastava *et al.* 2014; Materac *et al.* 2015).

Supported by a study led by Raskin & Ensley (2000), the effectiveness of rhizofiltration is substantiated, demonstrating that plant roots actively absorb contaminants and HMs from their surroundings. Furthermore, this technique can reduce the ability of sediment to carry metals, particularly in cases of excessive metal deposition (Radziemska *et al.* 2017; DalCorso *et al.* 2019; Bakshe & Jugade 2023). Rhizofiltration has proven successful in handling HMs such as Pb, Cu, Co, Cd, uranium (U), and As, which are often challenging to remove using conventional techniques. This economically viable and ecologically benign approach deploys plant roots to collect and eliminate these HMs from polluted water streams (Srivastava *et al.* 2021; Elehinafe *et al.* 2022).

Over the past decade, researchers worldwide have delved into rhizofiltration using various plant species, establishing its efficiency in eliminating HMs from wastewater. Table 2 provides a summary of researchers contributing to rhizofiltration technology, showcasing the diverse plant species employed for contaminant removal. This method underscores the adaptability and utility of rhizofiltration in long-term water remediation projects, emphasizing its role as an effective and sustainable solution for addressing water pollution.

Aquatic plants, such as water hyacinth (*Eichhornia crassipes*) and duckweed (*Lemna minor*), are widely used because of their great resistance to water contaminants. These are useful for up to 95% reduct (Kristanti & Hadibarata 2023; Zhou *et al.* 2023). For every tonne of dry biomass, plants can acquire 1–2 kg of HMs. Ponds and other little bodies of water can be treated by rhizofiltration. Biomass management and disposal requirements prevent it from being scaled to bigger aquatic bodies (Newete & Byrne 2016). Rhizofiltration is an efficient method for treating wastewater, although it has several drawbacks. The effectiveness of the technique could be jeopardized due to varying pollutant concentrations, which can be higher than the tolerance limit of plants (Kafle *et al.* 2022). It is important yet difficult to maintain ideal conditions, especially for large-scale applications, such as pH, temperature, and nutrient availability. The possibility of pollutants being released again into the environment through the roots of plants calls for cautious management and control methods (Bakshe & Jugade 2023).

The effectiveness and scalability of rhizofiltration as wastewater treatment technology have been the focus of recent improvements. The creation of specific plant species and hybrid systems that enhance the absorption and removal of pollutants from wastewater are examples of innovations (DalCorso *et al.* 2019). Plants with improved metal accumulation and tolerance have been created through genetic engineering. The efficacy of rhizofiltration has been boosted by its combination with other treatment techniques, including built wetlands and bioreactors. The microbial communities connected to plant roots have been optimized by developments in our knowledge of plant–microbe interactions, which have further enhanced the removal of contaminants (Thijs *et al.* 2016; Agrahari & Kumar 2024).

4.5. Phytovolatilization

Phytovolatilization represents a method in which pollutants are converted into hazardous compounds by green plants, utilizing the plant's stomata to release volatile substances into the surrounding environment (Pivetz 2001; Ghosh & Singh 2005; Leguizamo *et al.* 2017). Throughout this process, plants absorb pollutants from water or soil, converting them into less dangerous forms, and releasing them into the atmosphere. Plants naturally manage and transport numerous gases, including water vapor (H_2O), carbon dioxide (CO_2), oxygen (O_2), ethylene (C_2H_4), and signaling chemicals (Materac *et al.* 2015). The activation of systems that carry volatile organic compounds (VOCs) throughout the plant occurs based on the physiology of both the plant and the properties of the contaminant (Collins *et al.* 2006; Dettenmaier *et al.* 2009; Limmer & Burken 2014, 2016). Phytovolatilization finds frequent application in removing organic contaminants such as trichloroethylene (C_2HCl_3), benzene (C_6H_6), nitrobenzene ($C_6H_5NO_2$), phenol (C_6H_5OH), and atrazine ($C_8H_{14}ClN_5$) from soil and water, as well as HMs like Hg, selenium (Se), or As (Komives & Gullner 2005; Gonçalves *et al.* 2007; Wang *et al.* 2009).

Pollutants like Se and Hg are volatilized by plants like mustard and poplar. Under ideal circumstances, this process can volatilize up to 70–80% of certain pollutants. Depending on the kind of plant and surrounding conditions, the rate varies greatly; certain plants can release up to 50 g of Hg per hectare per year (Awgchew & Nigussie 2022). Areas with particular pollutants that may be safely volatilized can benefit from phytovolatilization (Qadir *et al.* 2020). The widely utilized wastewater treatment method known as phytovolatilization is restricted in its applicability due to a number of limitations. Potential volatile chemical releases into the atmosphere, which can lead to air pollution and endanger the health of those around, are a significant problem. Sites with a combination of contaminants or areas subject to stringent air quality laws are less appropriate for it. A number of variable environmental factors, including soil type, temperature, and humidity, as well as plant species, have a substantial impact on the effectiveness of this method (Limmer & Burken 2016).

The efficiency and efficacy of phytovolatilization as a wastewater treatment method have been the subject of recent improvements. By adding or overexpressing genes linked to the detoxification and emission processes, genetic engineering has been used to improve plants' capacity to volatilize toxins, such as HMs and organic pollutants (Kafle *et al.* 2022; Mamun *et al.* 2024). Plant species with stronger volatilization capacity and quicker growth rates have emerged as a result of improvements in plant breeding and selection. The more accurate manipulation of plant physiology has been made possible by advances in our knowledge of the molecular processes behind contaminant absorption, transport, and volatilization (Anas *et al.* 2020; Mahboob *et al.* 2023). To improve overall treatment efficiency, novel ways to combine phytovolatilization with other green technologies such as phytoremediation and artificial wetlands have also been investigated. As a result of all these developments, phytovolatilization is becoming a more viable and efficient wastewater treatment option.

As we navigate through the complexities of phytoremediation techniques, each method uncovers the unique role plants play in mitigating environmental contaminants. From phytoextraction's metal accumulation to phytodegradation's enzymatic breakdown of organics and the immobilization in phytostabilization, the upcoming section will delve into the critical aspect of selecting suitable plants for wastewater treatment. Understanding the diverse strategies employed by plants in phytoremediation mechanisms sets the stage for exploring how specific plant species, with their hyperaccumulation abilities, tolerance, and growth characteristics, become pivotal in constructing effective and sustainable solutions for wastewater treatment.

5. SELECTION OF SUITABLE PLANTS FOR WASTEWATER TREATMENTS

The remarkable capacity of plants to naturally accumulate HMs has gained increasing attention from the environmental science community and remediation approaches (Lajayer *et al.* 2019). This special ability arises from the intricate relationships between plants and the surrounding soil, where roots serve as the primary point of contact for metal absorption. HMs, including Zn, Pb, and Cd, are specifically absorbed by plants through a combination of metabolic and transport routes (Jabeen *et al.* 2009). These metals can be absorbed and stored in various plant parts, such as roots, leaves, and stems, creating a natural filtration system for pollutants in the soil. Effective wastewater treatment through phytoremediation hinges on the careful selection of plant species that exhibit specific traits conducive to the remediation process.

This section explores three pivotal aspects in the selection of suitable plants: hyperaccumulators, tolerance and adaption, and growth characteristics. Notably, certain plant species are termed hyperaccumulators, signifying their extraordinary ability to accumulate large quantities of HMs without experiencing harm (Muszyńska & Hanus-Fajerska 2015). The potential of leveraging this inherent ability to mitigate HM contamination in wastewater treatment through phytoremediation projects is considerable. Such projects offer a sustainable and environmentally friendly method for addressing the challenges associated with HM pollution.

By delving into the characteristics of hyperaccumulators and understanding their role in the phytoremediation process, researchers can strategically choose plant species that maximize metal accumulation in wastewater treatment scenarios. Table 3 presents the methods of phytoremediation, the mechanisms of pollutant removal, and the selection criteria for plant species. Additionally, considering the tolerance and adaptation mechanisms of plants in polluted environments, along with assessing growth characteristics, contributes to the development of robust and effective phytoremediation strategies. As we explore these critical aspects of plant selection, the subsequent sections will delve into the precise details of how these traits influence the success of wastewater treatment projects through phytoremediation.

5.1. Hyperaccumulators

Hyperaccumulators, a specific subclass of accumulator plants, are commonly found in naturally mineralized soils, showcasing a unique ability to collect elevated concentrations of metals in their leaves (Bhargava *et al.* 2012). Unlike other plants, hyperaccumulators can accumulate metals in their above-ground tissues without displaying any poisoning symptoms (Baker *et al.* 2020). These extraordinary plants are distributed across various regions, including Europe, North America, New Caledonia, and South Africa, thriving in soils abundant in metal content (Baker 1989).

The classification of a plant as a hyperaccumulator hinges on its capacity to accumulate metals beyond the Ni-toxicity threshold of 10–15 $\mu g\ g^{-1}$, with concentrations exceeding 1 $mg\ g^{-1}$ Ni in the shoot. Threshold values have been established for each HM based on its unique phytotoxicity, providing a systematic approach to characterizing hyperaccumulation (Rascio & Navari-Izzo 2011). The efficiency of hyperaccumulators in eradicating HMs from polluted soils is influenced by the rate of biomass generation and the bioconcentration factor (BCF), representing the ratio of metal content in soil to shoot tissue. The roots play a vital role in absorbing and cleansing metals while sustaining growth, absorption, and biomass generation (Guerinot & Salt 2001; Clemens *et al.* 2002; McGrath & Zhao 2003). Hyperaccumulators typically exhibit BCF values higher than 1, occasionally surpassing 50–100, sparking ongoing discussions about the relationship between metal hyperaccumulation and tolerance (Bhargava *et al.* 2012).

More than 0.2% of angiosperms, representing a significant proportion, display the remarkable phenomenon of hyperaccumulation of HM ions (Rascio & Navari-Izzo 2011). This phenomenon extends across a diverse range of more than 450 vascular plant species representing 45 angiosperm groups, including those within the *Cyperaceae*, *Asteraceae*, *Brassicaceae*, *Caryophyllaceae*, *Fabaceae*, *Cunoniaceae*, *Lamiaceae*, *Flacourtiaceae*, *Poaceae*, *Euphorbiaceae*, and *Violetaceae* families

Table 3 | Phytoremediation includes processes/mechanisms for contaminant removal and selection criteria of plant species (Yadav *et al.* 2018)

Approach	Pollutants	Mechanism	Selection criteria of plant species
Phytoextraction	Ni, Pb, Zn, Cd, Cu with EDTA addition for radionuclides, Pb, short chained aliphatic compounds, and pentachlorophenol	Hyperaccumulation	Tolerance to high metal-accumulation capability, high metal concentrations, accumulation of trace elements in above-ground parts, rapid growth rate, extended root system for exploring large soil volumes, easy to harvest, easy agricultural management, high translocation factor, resistance to pathogens and pests, good adaptation to prevailing environmental and climate conditions, repulse herbivores to avoid food chain contamination.
Phytodegradation	Herbicides – alachlor, atrazine, chlorinated aliphatic compounds – trichloroethylene (TCE), mixtures benzene toluene ethylbenzene and xylene (BTEX), nutrients – NH_4^+, NO_3^-, PO_4^{3-}, 2,4,6-trinitrotoluene (TNT), ammunition wastes, rapid detonating explosive (RDX)	Plant degradation	Vegetation should be easy to maintain, hardy and easy growing, tolerance to water logging and drought conditions, deep rooting plants such as willow, poplar, aspen, cottonwood etc., transform the toxic substances into less toxic or non-toxic products, and high transpiration rate.
Phytostabilization	Cd, Pb, As, Zn, Cr, Cu, U, Se, hydrophobic organics – polychlorinated biphenyl (PCBs), polycyclic aromatic hydrocarbons (PAHs), furans, dioxins, DDT, pentachlorophenol, dieldrin	Complexation	Ability to keep translocation of metals from roots to shoots as flat as possible, ability to develop extended and abundant root systems, capacity to retain contaminants in roots or rhizosphere (excluder mechanism).
Rhizofiltration	Heavy metals such as Cd, Pb, Ni, Zn, Cu, Radionuclides – Sr, Cs, hydrophobic organics, U, and radionuclides	Rhizosphere accumulation	High adsorption surface, metal-resistant plants, terrestrial plants preferred because of fibrous and much longer root system, tolerance of hypoxia,
Phytovolatilization	Chlorinated solvents like trichloroethylene, carbon tetrachloride, tetrachloroethylene, methylene chloride, 1,1,1-trichloroethane, carbon tetrachloride, Se, Hg ion	Volatilization by leaves	Contaminants could be transformed to less-toxic substances, Hg ion may be transformed into less-toxic substance, ability to use terrestrial/aquatic plants for, *ex-situ* or *in-situ* application, species other than hyperaccumulators may be used, metabolites or contaminants released to atmosphere subject to more effective or rapid natural degradation processes (such as photodegradation).

(Padmavathiamma & Li 2007). Beyond their ecological and physiological significance, the interest in hyperaccumulator plants has surged due to the potential utility of their accumulation features. This interest opens avenues for practical applications, like the development of phytoremediation techniques for wastewater treatment or HM-contaminated soils (Rascio & Navari-Izzo 2011).

5.2. Tolerance and adaptation

Within the realm of phytoremediation, the success of plants in remediating formidable environmental conditions hinges on their resilience, illustrated by a delicate interplay of tolerance and adaptation. With an increase in contamination, plants demonstrate their capacity to withstand heightened pollutant levels and adjust to the distinctive conditions prevalent in wastewater environments (Mahar *et al.* 2016). As HM ions permeate the cellular domain, plants deploy sophisticated tolerance strategies to counteract the associated toxicity (Dalvi & Bhalerao 2013). Detoxification becomes crucial when surplus HM ions accumulate within the cytosol, compelling plants to mitigate their toxic effects. This intricate process involves chelation, where HM ions form complexes with ligands, diminishing the concentrations of free metal ions to benign levels (Manara 2012).

Various inorganic and organic ligands within the cytoplasm play pivotal roles in mediating HM chelation, encompassing metallothioneins, organic acids, phytochelatins, amino acids, and cell wall polyphenols/pectins/proteins (Gupta *et al.* 2013). For example, by complexing and decreasing the bioavailability of HM, organic acids stop them from remaining free ions in the cytoplasm. This intricate interplay of tolerance mechanisms and adaptive responses unveils plants' remarkable ability to navigate and mitigate the challenges posed by diverse contaminants, offering profound insights into the selection of robust species for effective phytoremediation (Yan *et al.* 2020).

5.3. Growth characteristics

In the realm of phytoremediation, the growth characteristics of chosen plants emerge as pivotal determinants of wastewater treatment efficacy. Factors like rapid growth (Abdelkrim *et al.* 2019), extensive root systems (Abdelhameed & Metwally 2019), and significant biomass yield are instrumental contributors to the efficient removal of pollutants (Aken 2008). These desirable growth attributes not only enhance the overall phytoremediation process but also facilitate cost-effective and sustainable approaches to wastewater treatment. A profound understanding and effective utilization of the growth characteristics specific to each plant species become imperative for optimizing their potential in environmental cleanup endeavors.

The ability of hyperaccumulator plants to flourish under elevated levels of HM can be attributed to multiple biochemical pathways that help maintain lower metal concentrations in the cytoplasm as compared to the soil, safeguarding cytoplasmic organelles from the toxic effects of HMs (Nedjimi 2009). Hyperaccumulator plants efficiently accumulate substantial quantities of HMs in their above-ground parts during normal growth and reproduction, with some exhibiting the capacity to accumulate non-essential HMs, such as Pb, Ag, Cd, and Hg, which lack functions (Nedjimi & Daoud 2009). The efficacy of phytoextraction is further heightened by plants with a high growth rate, resulting in a huge quantity of plant biomass coupled with a deeper root system (Nedjimi 2021).

6. CASE STUDIES ON PHYTOREMEDIATION

Phytoremediation is an environmentally friendly and sustainable method to clean up contaminated environments. It has been successfully used in various case studies. Remediating HM-contaminated soils with hyperaccumulator plants, such as *Alyssum* species, is one prominent example (Li *et al.* 2003). By accumulating and concentrating metals like Zn and Ni in their tissues, these plants have demonstrated the potential to lower soil metal concentrations. Wetland plants, for instance, Phragmites australis, have also been successfully used to cleanse water tainted with contaminants like petroleum hydrocarbons (Williams 2002). A thorough model for wastewater stabilization pond optimization is provided by Ali & Üçüncü (2023), which provides insightful information on enhancing the effectiveness of wastewater treatment methods, such as phytoremediation. Tahiri *et al.* (2023) assesses the presence of pharmaceutical compounds in wastewaters and aquatic environments, highlighting the need for effective treatment solutions such as phytoremediation to address emerging contaminants. In order to assess the efficacy of phytoremediation in enhancing groundwater safety and lowering health risks, Nguyen & Huynh (2023) provide a thorough description of groundwater quality and relate it to human health. These case studies demonstrate how phytoremediation may be used to remediate polluted land and water in a sustainable manner, highlighting its adaptability in tackling a variety of environmental issues. A comprehensive understanding of phytoremediation through a detailed bibliographical table featuring additional case studies is displayed in Table 4.

7. ADVANTAGES AND CHALLENGES OF PHYTOREMEDIATION

As a potential technique for cleaning up the environment, phytoremediation has a number of advantages and implementation-related challenges. One significant advantage is that it is environmentally friendly since plants use their own natural mechanisms to remove pollutants, which reduces the need for large-scale infrastructure (Futughe *et al.* 2020; Lata & Siddharth 2021). Furthermore, phytoremediation is economical, particularly in contrast to more conventional remediation techniques. The technique also improves esthetics, as well-chosen plants enhance the esthetic appeal of green places and aid in ecological restoration (Farraji *et al.* 2016).

There are obstacles in the way of widely using phytoremediation, though. In order to see significant effects, the approach might be lengthy and patient (Babu *et al.* 2021). Based on site-specific factors including soil composition and climate, phytoremediation's efficacy may differ (Jaskulak *et al.* 2020). It is important to select the right plant species for the area and toxins present, and the possibility of contaminants being released back into the ecosystem after plants are harvested is one of the

Table 4 | Bibliographical table on various case studies

Type of water	Plant species used	Pollutants	Concluding remarks	References
Wastewater	*Lemna minor*	Dyes (Congo red and methylene blue)	After a 24-day period, it decreased Congo red by up to 25% and methylene blue by up to 99%.	Wibowo *et al.* (2023a, 2023b)
Household and Industrial wastewater	Water lettuce (WL), pennywort (PW), duckweed (DW), and alligator weed (AW)	Pb, Zn, ammonia (NH_3), PO_4, sulfate (SO_4), potassium (K)	Compared to other treatments, AW was shown to have the greatest potential for phytoremediation.	Raza *et al.* (2023)
Swine wastewater	*Pistia stratiotes*	Cu	It was shown that NO controls the phytoremediation of wastewater for Cu.	Liu *et al.* (2023)
Textile wastewater	*Spirodela polyrhiza* (L.) Schleid.	COD, color, calcium (Ca), Fe, Ni, Cd, nitrate (NO_3), PO_4, SO_4,	Final reduction up to 77.36, 91.70, 61.65, 69.41, 89.30, 88.37, 70.83, 73.11, and 75.49%, respectively.	Parihar & Malaviya (2023)
Wastewater	*Pistia stratiotes* and *Eichhornia crassipes*	BOD, Fe, COD, Mn, PO_4, NH_4, NO_2, NO_3	They are potential plants for phytoremediation.	Wibowo *et al.* (2023a)
HMs-contaminated wastewater	*Amaranthus hybridus* (Indian *cholai*)	HMs (Ni, Fe, Sr)	*A. hybridus* has the possibility to be a Fe, Sr, and Ni hyperaccumulator.	Jha *et al.* (2023)
Antibiotics-contaminated wastewater	Coontail (*Ceratophyllum demersum*)	Tetracycline	Coontail is suitable for managing antibiotic-contaminated waste water.	Ali *et al.* (2023)
Antibiotic-contaminated water	*Cyperus papyrus*	Fluoroquinolone	A progressive recognition of phytoremediation methods.	Chen *et al.* (2023)
Dairy wastewater	Water fern (*Azolla pinnata* R. Br.)	pH, electrical conductivity (EC), TDS, TP, total Kjeldahl's and, N	Maximum significant reduction efficiency of pollutants ($p < 0.05$)	Goala *et al.* (2021)
Olive mill wastewater	*Myrtus communis* L. and *Punica granatum* L.	Organics, phenolics, TN, and TP	It was observed that elimination rates were around 10 times higher.	Petoussi & Kalogerakis (2022)
Pulp and paper industry wastewater	*Momordica doica* and *Cannabis sativa*; *Tribulus terrestris and P. hysterophorus*	HMs (Fe, Cd, As, Cr)	Most of the indigenous plants had hyperaccumulating tendencies.	Sharma *et al.* (2021)
Well water and treated wastewater	Vetiver (*Chrysopogonzizanioides*), Pampas (*Cortaderiaselloana*)	Total hardness (TH), TDS	Compared to employing vetiver for phytoremediation, the use of Pampas grass for surface and subsurface drippers and for both kinds of water is much greater ($P < 0.05$).	Mirzaee *et al.* (2021)
Sulfonamides polluted wastewater	*Cyperus papyrus*	Sulfonamides	The results confirm that sulfonamides can be bioremediated and offer fresh information on what happens to sulfonamides throughout the phytoremediation process.	Chen *et al.* (2021)
Paperboard mill wastewater	Vetiver grass (*Chrysopogon zizanioides*)	EC, TDS, total soluble salts, COD, BOD, TN, P, K, Pb, Cd	It has a bright future for creating an economical, long-lasting process for detoxifying pollutants from wastewater produced in paperboard mills.	Davamani *et al.* (2021)

(*Continued.*)

Table 4 | Continued

Type of water	Plant species used	Pollutants	Concluding remarks	References
Olive mill wastewater	*Cyperus alternifolius* L. and *Vertiveria zizanioides* (L.) Nash	Total organic compounds (TOC), TN, phenolic compounds	These species may be employed as an environmentally friendly way to clean effluent from high-strength olive mills that has been diluted.	Goren *et al.* (2021)
,Secondary treated domestic wastewater	*S. molesta*	N and P	The S. molesta plants weighing the most (280 g) were more effective in eliminating the extra nutrients found in the influent samples.	Mustafa & Hayder (2021))
,Pulp and paper industry wastewater	*Bacillus* sp. PS-6	Fe, Pb, Ni, Mn, Zn, Cu, Cd, and As	The reduction of HM levels in wastewater following in-situ phytoremediation was demonstrated by the results.	Sharma *et al.* (2021)
Urban wastewater	Water hyacinths	Greenhouse gases	The findings imply that even in challenging circumstances, water hyacinths had strong capabilities for removing N and P.	Qin *et al.* (2020)
Dairy wastewater	Macrophytes (*Cyperus articulates*, *Eichhornia crassipes*, *Eleocharis interstincta* and *Typha domingensis*)	BOD, TP, TN	Dairy wastewater may be treated and its nutrients cycled using aquatic macrophytes.	Queiroz *et al.* (2020)

challenges. Despite these challenges, further study and technical developments hope to increase phytoremediation's effectiveness and adaptability, making it a practical and long-term solution for dealing with environmental pollution. To optimize phytoremediation's potential in various remediation circumstances, it is essential to comprehend both the potential advantages and challenges.

8. COMPARATIVE ANALYSIS OF PHYTOREMEDIATION TECHNIQUES IN WASTEWATER TREATMENT

There are several wastewater techniques available through phytoremediation, each having advantages and disadvantages of their own. The most important factor to compare when contrasting various strategies is their efficacy. Heavy metals like Ni and As are effectively removed from wastewater by hyperaccumulators such as *Alyssum* and *Pteris vittate* (Sytar *et al.* 2020). Wetland plants that use phytoextraction and biosorption, such as *Junicus* (rush) and *Typha* (cattail), are also good at eliminating heavy metals (Ali *et al.* 2020). While certain species, like *Vetiveria zizanoides* (vetiver) and *Salix* (willow), can breakdown pesticides and solvents by phytodegradation (Khan *et al.* 2020; Kafle *et al.* 2022).

The growth conditions of various plants are important factors in determining their efficiencies. *Eichhornia crassipes* (water hyacinth) and *Lemna* (duckweed) are examples of hydrophytes that do well in wet environments and are excellent at removing nutrients (Lu *et al.* 2018). They do, however, need steady water levels and may grow invasive. Because they are suited to land-based systems, terrestrial plants like *Sorghum* and *Rudbeckia* are helpful in the treatment of industrial wastewater. For these plants to flourish, more watering and soil amendments might be needed (Gawronski *et al.* 2011).

The viability of phytoremediation is also affected by maintenance and management issues. Perennials need less frequent replanting but can be more difficult to manage than annuals due to their slower growth rates, which make them simpler to harvest yet necessitate replanting every season. Different plants have different nutritional requirements. Others require high nutrient levels for optimal development, which might be difficult to achieve in nutrient-poor wastewater. On the other hand, other plants can survive with low nutrient levels but may be less efficient in removing contaminants (Ajayi & Ogunbayio 2012; Slocombe *et al.* 2020).

A key consideration in the decision-making process is cost and economic viability. The selection of plants, preparation of the site, and installation might result in significant upfront expenses when putting up a phytoremediation system. This initial cost can be minimized, though, by selecting inexpensive or native plants (Fernandez 2014). Phytoremediation sometimes uses less energy than certain mechanical or chemical treatment techniques, but operational expenses still include possible replanting, harvesting, and continuous upkeep.

9. FUTURE PROSPECTS

Sustainable wastewater management needs innovation and improvements in the field of phytoremediation. Plants that have undergone genetic modification may be better able to absorb and break down pollutants. Hybrid systems provide comprehensive purification solutions by integrating phytoremediation with other techniques. The global reach of phytoremediation is increased by robust plant species that flourish in a variety of temperatures. Economic analysis shed light on large-scale, cost-effective solutions. A climate that is ready for adoption is nurtured by regulatory frameworks. The modern monitoring systems guarantee real-time effectiveness evaluation. The initiatives for public education spread the seeds of knowledge about the ecological effects of phytoremediation. The green solutions are incorporated into urban areas for sustainable development through integration with urban planning. Phytoremediation helps in purifying water sources by addressing HMs and newly discovered pollutants. Phytoremediation is expected to be a key component of sustainable wastewater treatment in the future.

Phytoremediation is more practically feasible in locations with appropriate soil and climate since plants need certain conditions to grow and eliminate pollutants. Sites that face severe environmental conditions or high pollution levels may provide difficulties that reduce the viability of phytoremediation. A disadvantage for circumstances needing quick cleanup is that phytoremediation often works over a longer period of time than more instantaneous chemical or mechanical treatments. Therefore, even if the technique seems promising, its use will rely on technological considerations as well as a thorough site evaluation and timeline consideration.

Several policy recommendations might be taken into consideration to facilitate the application of phytoremediation techniques:

(1) Governments ought to offer grants and financial incentives for the advancement of phytoremediation technology research and development. Through this investment, biotechnology, plant breeding, and hybrid treatment technologies may all be advanced and made more widely available and efficient.
(2) Adoption of phytoremediation in the management of polluted sites might aided by the establishment of precise rules and regulations. Policies should guarantee that pollutants are adequately handled and disposed of, as well as the safe management of plant biomass.
(3) Encouraging cooperation between government, business, and academic institutions can result in the creation of creative ideas and the effective execution of phytoremediation initiatives. Collaborations can facilitate the exchange of best practices, resources, and information.
(4) By raising understanding of the advantages and drawback of phytoremediation, public education campaigns can help these technologies gain traction and acceptability. Adoption can also be accelerated by educating industry executives and legislators about successful case studies.
(5) Promoting pilot initiatives and testing grounds can yield important information on how well phytoremediation works under different circumstances. These initiatives can direct larger-scale deployments and contribute to the development of technological confidence.

Policymakers may handle environmental pollution more effectively and sustainably by addressing these factors and fostering an atmosphere that encourages the development and use of phytoremediation.

10. CONCLUSION

Phytoremediation, which includes important technologies including phytoextraction, rhizofiltration, phytostabilization, phytodegradation, and phytovolatilization, is a very flexible and sustainable wastewater treatment method. Phytoextraction is a promising approach that can successfully treat HM contamination through the use of hyperaccumulator plants. The case studies that are being presented highlight the practical success of phytoremediation in a variety of wastewater, demonstrating both its cost-effectiveness and environmental friendliness in addressing the problems associated with water pollution worldwide. The use of plants in remediation strategies – especially when it comes to techniques like phytoextraction – offers hope for a cleaner and greener future as we navigate the terrain of environmental stewardship and makes a significant contribution to the discussion about sustainable wastewater treatment methods.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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