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# The physiological and ecological characteristics of some phytoremediation plants for wastewater treatment: a review

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**ABSTRACT**

Phytoremediation has emerged as an effective method for mitigating heavy metal contamination in waterways. This study synthesizes literature to assess the physiological and ecological characteristics enhancing the efficiency of five plant species traditionally recognized for their phytoremediation potential: Napier grass (*Pennisetum purpureum*), *Phragmites australis, Typha* spp*., Pistia stratiote*s, and *Eichhornia crassipes*. A systematic review methodology was utilized, focusing on data from Proquest, EBSCO, and Scopus, prioritizing studies based on pollutant absorption capacities, publication quality, and recency. Key parameters examined include the identification of plant species, growth conditions, pollutant absorption efficiency, ecological roles, and physiological characteristics. *Phragmites australis* is noted for its nutrient uptake and sediment stabilization, while *Eichhornia crassipes* demonstrates high heavy metal absorption and rapid growth. *Pistia stratiotes* effectively removes heavy metals and enhances water quality, and *Typha* spp. aids in nutrient removal while providing habitat. Napier grass contributes to biomass production and soil stabilization. The integration of these species into wastewater treatment systems not only improves water quality but also fosters sustainability and ecological health. This study emphasizes the potential utility of these plants in environmental management initiatives, highlighting the necessity for careful monitoring to mitigate associated ecological risks.



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## 1. INTRODUCTION

Numerous studies have shown how aquatic plants, like *Phragmites australis* and water hyacinth (*Eichhornia crassipes*), can effectively reduce heavy metal concentrations in contaminated water through phytoremediation processes [1]–[3]. Furthermore, phytoremediation is a desirable substitute for traditional remediation methods due to its ecological and economic sustainability, which restores contaminated ecosystems while reducing expenses and environmental impact [4]. The potential of various plant species and their combinations to maximize the phytoremediation process is still being investigated to provide a thorough approach to environmental restoration [5].

For potential phytoremediators to be effective in contaminated environments, understanding their ecological characteristics is essential. Biomass production, growth rate, and adaptability are the main determinants of pollutant uptake and accumulation. For example, because of its capacity for survival and reproduction, *Phragmites australis* has demonstrated resilience in contaminated environments, suggesting it is potential as a phytoremediator [6]. Additionally, to maximize the results of phytoremediation, plant species must be chosen based on functional characteristics like root architecture and nutrient uptake efficiency [7]. Knowing these characteristics can help identify species that have a high capacity for pollutant accumulation, in addition to thriving in contaminated environments. The effectiveness of phytoremediation is greatly increased by physiological characteristics such as metal tolerance mechanisms and symbiotic relationships with advantageous microorganisms, especially in wastewater treatment. The production of chelating agents like phytochelatins and metallothioneins, which aid in detoxifying metals and lowering their cytotoxicity, is one of the physiological adaptations that plants display to deal with heavy metal stress [8], [9].

Additionally, by changing metal bioavailability and boosting nutrient uptake, the association with plant growth-promoting bacteria (PGPB) can reduce metal toxicity and increase plant resilience in contaminated environments [10], [11]. Since mycorrhizal fungi can decrease plant uptake of metals and promote plant growth in metal-polluted environments, their role in promoting metal tolerance is also crucial [12]. This symbiotic relationship is an essential part of phytoremediation strategies because it not only helps stabilize contaminants but also supports the general health of the plant [13]. Therefore, the efficacy of phytoremediation in the treatment of heavy-metal-contaminated wastewater can be greatly increased by incorporating these physiological characteristics and microbial partnerships. The novelty of this study lies in its trait-based classification and ecological suitability mapping of these species, advancing knowledge on their utility in phytoremediation. By addressing the gap in comprehensive reviews, this research reveals that *Phragmites australis* excels in nutrient uptake and sediment stabilization, while *Eichhornia crassipes* and *Pistia stratiotes* are noted for their heavy metal absorption capabilities.

## 2. METHOD

### 2.1. Databases searched

This research methodology focused on data collection from previously published works. Proquest, EBSCO, and Scopus, leading and well-known databases, served as primary data sources. These databases were selected for their track record of providing peer-reviewed journals, articles, and scientific publications, ensuring the accuracy and reliability of the collected data. This study relied on a thorough investigation of various scientific databases to gather reliable data on pollutant-absorbing capacity of various plant species.

### 2.2. Article selection criteria

Relevance to the study topic concerning plant species and their capacity to absorb pollutants is one of the requirements that must be met by the articles chosen for review. Publication in an influential journal that is well known in the environmental sciences, botany, or ecology fields. A date of publication that is relatively recent to guarantee that the data are up-to-date and pertinent. The selection of articles for this study was governed by stringent criteria aimed at ensuring both the relevance and quality of the data. Firstly, the relevance criterion mandated that only articles specifically addressing the ability of distinct plant species to absorb pollutants, including heavy metals and organic compounds, be included. Second, the publication source criterion restricted the selection to articles appearing in high-impact, peer-reviewed journals, ensuring the works are recognized within the domains of environmental science, botany, and ecology. Additionally, a recency criterion required that selected publications be from the last decade, thereby affirming the applicability of findings to current environmental issues. Upon meeting these criteria, articles underwent a meticulous review process to verify their relevance and methodological robustness, solidifying the foundation of this research endeavor.

### 2.3. Keyword used

The keywords used in this literature review include terms and phrases relevant to the species and the research topic, namely the ability of plants to absorb pollutants, such as phytoremediation, pollutant absorption capacity, heavy metals, and organic compounds. Additional keywords cover plant and environmental aspects: plant species, environmental factors, soil types, humidity, temperature, lighting, biodiversity, ecosystem sustainability, ecological roles, and morphological and physiological adaptations. The use of these keywords aims to clarify the research focus and facilitate the search for relevant literature in scientific databases, as described in the methodology section.

### 2.4. Data separation based on parameters

This study identified several important parameters in this study that are pertinent to the analysis of plant species. To ensure accurate identification, the studied plant species were first identified along with their scientific names and potential synonyms. Environmental elements that affect plant growth, such as soil type, humidity, temperature, and lighting, are described in detail. The primary focus is on the pollutant uptake capacity, where analysis is performed to determine how well a plant species absorbs specific pollutants, such as organic compounds and heavy metals. Common uses for plant species have also been documented, including reforestation, land rehabilitation, and ornamental plant use. The ecological role of plant species is explained by highlighting their effects on biodiversity, interactions with other species, and contribution to the ecosystem. Important traits of plant species, such as morphological or physiological adaptations, set them apart from other species. To understand how plant species respond to environmental stress and what adaptations are necessary for survival, physiological and ecological characteristics are examined.

### 2.5. Data analysis

This study conducts a thorough analysis of the data, divided according to predefined criteria. The findings of the analysis are organized in a table that provides data in a methodical manner, making comparison and data visualization easier. All the identified parameters are included in this table so that readers can rapidly comprehend the data being presented. To provide a more comprehensive picture of plant species' ecological roles and their capacity to absorb pollutants, a synthesis of the results from numerous reviewed studies was also conducted. By combining the findings of multiple studies, this synthesis process makes it possible to identify important patterns and trends in the relationships between different plant species and their surroundings. Therefore, in addition to presenting the data, this study offers deeper insights into how plant species contribute to ecosystem sustainability and pollution mitigation.

### 2.6. Presentation of results and discussion

The results and discussion section contains the findings of the data analysis. Here, the authors discuss the implications of the results, link the findings to pertinent theories, and offer suggestions for additional studies. Comparisons with earlier research and an explanation of how the findings of this study can advance knowledge of relationships between plants and their surroundings are also included in discussion.

## 3. RESULTS AND DISCUSSION

The physiological and ecological characteristics of several plant species with phytoremediation potentials are listed in Table 1. Water hyacinth (*Eichhornia crassipes*) is a plant that grows well in warm watery habitats and has a high capacity to absorb heavy metals, which makes it useful for animal feed and water purification. The broad root system and rapid growth improve pollutant removal and nutrient uptake. Wetlands and marshy areas are home to *Phragmites australis* or common reed, which exhibits a moderate capacity to absorb pollutants. A strong root system that stabilizes sediments and sustains a variety of microbial communities is essential for wetland restoration and erosion control. *Pistia stratiotes* is known for its ornamental use and moderate nutrient uptake, and they grow in freshwater habitats. The high photosynthetic rate and ability to adapt to different conditions make it an excellent nutrient filter. Wetlands and shallow waters are home to *Typha* spp. (cattails), which provides moderate pollutant absorption and wildlife habitats. Their vast root system improves nutrient removal and water filtration. Napier grass (*Pennisetum purpureum*) is mostly used as an animal feed in well-drained soils. It has a deep root system that helps stabilize the soil, increases microbial activity, and absorbs pollutants at a low to moderate rate. By providing habitats, enriching the soil, and cleaning up pollutants, these species work together to promote ecological health.

Table 2 showed *Eichhornia crassipes* exhibits a high uptake capacity for heavy metals such as lead (Pb), cadmium (Cd), and zinc (Zn), with rapid biomass growth, but its presence can be invasive. *Phragmites australis* exhibits strong tolerance to salinity and heavy metals, but its invasive variants can disrupt local ecosystems. *Pistia stratiotes* uptakes heavy metals efficiently but requires careful management due to its invasive potential. *Typha* spp. have moderate uptake capacity but can dominate native flora. Finally, Napier grass has a variable capacity for heavy metals and contributes to soil stability, although it can be invasive in some areas.

### 3.1. *Eichhornia crassipes*

*Eichhornia crassipes*, commonly known as water hyacinth, exhibits remarkable potential for phytoremediation in both tropical and temperate aquatic ecosystems. The rapid growth rate and ability to enhance dissolved oxygen (DO) levels facilitate the reduction of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in contaminated waters [14]. Studies indicate that *Eichhornia crassipes* can effectively remove heavy metals such as Pb, Cd, and Zn from aquatic environments, showcasing its applicability in bioconcentration processes [15]. Furthermore, while its introduction as a non-native species can enhance phytoremediation efforts, it poses significant ecological risks by potentially outcompeting native plant species and disrupting local ecosystems. As such, managing *Eichhornia crassipes* populations is critical to ensuring both its benefits for water treatment and the preservation of indigenous biodiversity.

Table 1. Physiological and ecological characteristics of possible phytoremediators

| Plant species | Growth conditions | Pollutant absorption capability | Common uses | Ecological role | Notable characteristics | Physiological and ecological treat |
|---|---|---|---|---|---|---|
| *Eichhornia crassipes* | Aquatic, warm climates | High for heavy metals | Purification of water and animal feed | Habitat for aquatic life | Effective in reducing BOD and COD, with high adsorption capacity, and antimicrobial effects | High nutrient uptake capacities, extensive root systems, and rapid growth rates allow for the efficient removal of pollutants. |
| *Phragmites australis* | Wetlands, marshy areas | Moderate | Erosion control and wetland restoration | Habitat for wildlife | Tall, perennial grass that stabilizes sediments and is effective at absorbing nutrients | Large root systems, high biomass production, photosynthetic capacity, rates of transpiration, and adaptability to high CO2 levels maintain diverse microbial communities, stabilize sediments, and increase resistance to Environmental Stressors. |
| *Pistia stratiotes* | Freshwater environment | Moderate | Filtration of water for ornamental use | Gives aquatic species cover | A floating aquatic plant that grows quickly and effectively absorbs nutrients | High net photosynthetic rate, allowing for quick biomass production and adaptability to different environmental factors, such as light and nutrient levels, pollutant tolerance, dense root network, potential invasiveness, and absorption capacity of heavy metals. |
| *Typha* spp. | Wetlands, shallow waters | Moderate | Biofuel and wetland restoration | Habitat for birds and insects | Tall, reed-like plants that filter water effectively and help create habitat | Large root systems, high contamination tolerance, effective nutrient removal, quick growth, and flexibility. |
| Napier grass | Well-drained soils | Low to moderate | Control of erosion and livestock feeding | Soil stabilization | High production of biomass, resistant to drought, mainly used for fodder | The deep root system's extensive root system, rapid growth, and high biomass production can all improve the quality of the soil and microbial activity. |

Table 2. Summary of physiological and ecological characteristics of selected phytoremediators

| Plant species | Uptake capacity | Growth rate | Tolerance thresholds | Ecological resilience |
|---|---|---|---|---|
| *Eichhornia crassipes* | High for heavy metals (Pb, Cd, Zn) | Rapid increase in biomass (up to 15.1% in wastewater) | High tolerance to nutrient levels | Can become invasive, impacting native species |
| *Phragmites australis* | Moderate for heavy metals and nutrients | Adaptable, thriving in diverse wetlands | Strong resistance to salinity and heavy metals | Supports microbial diversity, but invasive variants can disrupt local ecosystems |
| *Pistia stratiotes* | Efficiently absorbs heavy metals (Pb, Cd, Cr) | Rapid growth in nutrient-rich waters | High tolerance to pollutants | Can be invasive; careful management required |
| *Typha* spp. | Moderate, effective for various pollutants | Rapid growth; adapts well to various environments | High tolerance to salinity and fluctuating water levels | Can outcompete native flora, affecting biodiversity |
| Napier grass | Low to moderate for heavy metals | Rapid growth with high biomass production | Resilient to nutrient-rich and contaminated environments | Supports soil stability, but can be invasive in certain areas |

Water hyacinth (*Eichhornia crassipes*) is a free-floating aquatic macrophyte that has attracted considerable interest because of its potential applications in phytoremediation and wastewater treatment. Rapid growth rates, extensive root systems, and high nutrient uptake capabilities are just a few of the ecological and physiological characteristics that make them a strong contender for the removal of different pollutants from contaminated water bodies. Numerous studies have demonstrated the capacity of plants to improve water quality by lowering COD, BOD, and heavy metal removal. A view of *Eichhornia crassipes* is shown in Figure 1.

Figure 1. *Eichhornia crassipes* adopted from [16]

*Eichhornia crassipes* photosynthetic activity, which raises the DO levels in water, is one of the main ways it aids in wastewater treatment. By creating conditions that support aerobic bacterial activity, this increase in DO contributes to a significant decrease in BOD and COD levels. Heavy metals can be effectively removed from water contaminated by *Eichhornia crassipes*. According to previous studies, it can absorb significant concentrations of metals from aquatic environments, including Pb, Cd, and Zn. For instance, Zhou *et al.* [17] discovered that the plant could efficiently extract heavy metals from karst water, proving its ability to bioconcentrate even at low levels of these contaminants.

Furthermore, *Eichhornia crassipes* has a notable capacity for biomass production in wastewater treatment. According to Dölle *et al.* [18], the plant could quickly increase its biomass, with growth rates in municipal wastewater up to 15.1%. In addition to helping with the treatment process, this quick biomass buildup offers a sustainable resource that can be harvested for a number of uses, such as the creation of biogas and organic fertilizers [19].

The possible ecological hazards associated with the introduction of *Eichhornia crassipes* into non-native habitats must be understood. It can outcompete native plants as an invasive species, reducing biodiversity and altering ecosystem dynamics 29. Therefore, to reduce these risks and utilize the phytoremediation potential of plants, careful management and monitoring are required.

**3.2. *Phragmites australis***

*Phragmites australis*, commonly known as common reed, exhibits significant ecological adaptability, making it a prominent candidate for phytoremediation across diverse geographic regions, including temperate and tropical climates. This species demonstrates remarkable phenotypic plasticity, allowing it to thrive in a variety of wetland habitats, from coastal marshes to inland water bodies, and is often resilient in areas with heavy metal contamination and salinity stress [20], [21]. Notably, its clonal growth via rhizomes helps stabilize sediments, facilitates nutrient cycling, and supports diverse microbial communities essential for pollutant degradation [21].

There are substantial differences between native and invasive populations of *Phragmites australis*, particularly in their ecological roles and effects on local biodiversity. Native populations typically contribute positively to ecosystem health, while invasive variants can outcompete local flora, reduce biodiversity, and disrupt ecological balance [22]. The ecological dynamics of these populations often vary with geographical and climatic conditions, suggesting that management strategies need to be tailored based on specific environmental contexts [22], [23].

Common reed, or *Phragmites australis*, is a multipurpose wetland plant that has drawn a lot of interest owing to its physiological and ecological characteristics, especially when it comes to wastewater treatment. This species is a good candidate for phytoremediation because of its exceptional capacity to flourish in various environmental settings. The large root system and high biomass production make it effective at eliminating heavy metals, organic and inorganic pollutants, and nutrients like phosphorus and nitrogen from wastewater [24], [25]. Figure 2 shows a view of *Phragmites australis.*

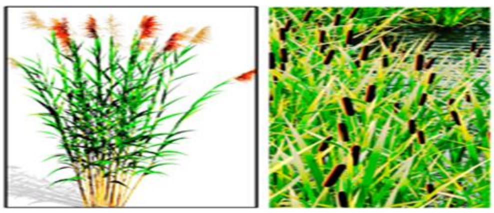

Figure 2. *Phragmites australis* adopted from [26]

The physiological traits of *Phragmites australis* are essential for its capacity to purify wastewater. The growth and effectiveness of pollutant uptake depend on the photosynthetic capacity and transpiration rate of the plant. Research has indicated a strong correlation between *Phragmites Australis*'s growth performance and its capacity to improve nitrogen removal through denitrification processes in artificial wetlands [24], [25], [27]. Additionally, the ability of the plant to adjust to higher $CO_2$ levels has been linked to improved COD and total nitrogen removal efficiencies in artificial wetlands, suggesting that atmospheric conditions can have a substantial impact on the plant's wastewater treatment capabilities [27].

The ecological characteristics of *Phragmites australis* also enhance its efficacy in wastewater treatment. In addition to stabilizing sediments, the plant's vast rhizome system supports a varied microbial community that improves pollutant degradation and nutrient cycling [28]. The mineralization of organic nitrogen and the nitrification-denitrification processes, which are necessary for efficient nitrogen removal, depend on the interaction between *Phragmites australis* and microbial populations [27]. The efficiency of pollutant removal by plants is also affected by their growth dynamics, which are influenced by seasonal variation. Higher rates were observed during the summer months, when growth was the most vigorous.

Furthermore, *Phragmites australis* can flourish in contaminated environments because of its exceptional resistance to a range of environmental stressors, such as salinity and heavy metal contamination [21]. Their ability to adapt is essential for their use in artificial wetlands, where they can efficiently treat wastewater under a variety of geographic and climatic conditions. The plant's suitability for wastewater treatment is further enhanced by its capacity to grow in anaerobic environments, which allows it to continue metabolic processes even in low-oxygen environments [21].

Incorporating *Phragmites australis* into wastewater treatment systems improves pollutant removal and supports the general ecological well-being of wetland habitats. By fostering microbial diversity and offering habitat for a variety of aquatic organisms, the plant supports biodiversity, which is crucial for preserving ecosystem functions [29]. Additionally, using *Phragmites australis* in artificial wetlands can result in the development of blue carbon ecosystems, which are important for mitigating climate change and sequestering carbon [30].

*Phragmites australis* is a successful plant for treating wastewater because of its physiological characteristics, ecological adaptability, and capacity to accumulate and eliminate broad variety of contaminants. The use in artificial wetlands contributes to the ecological integrity of wetland systems and improves the water quality. The mechanisms underlying its capacity to remove pollutants and possibility of maximizing its use in a range of wastewater treatment applications should be further investigated in future studies.

### 3.3. *Pistia stratiotes*

*Pistia stratiotes*, commonly known as water lettuce, demonstrates significant potential for wastewater treatment through phytoremediation due to its ecological and physiological traits. Its extensive root system facilitates the absorption of heavy metals such as Pb, Cd, and chromium (Cr) from contaminated water sources, highlighting its effectiveness in pollutant removal [31]. Moreover, the plant's rapid growth allows it to thrive in nutrient-rich environments typical of polluted waters, enhancing its biomass accumulation, which is advantageous for wastewater treatment [32].

Geographically, *Pistia stratiotes* is predominantly found in tropical regions, where it can become invasive, potentially disrupting local ecosystems [33]. The propensity for rapid growth can Pb to concerns regarding its invasion of non-native areas, necessitating careful management strategies to mitigate ecological impact [34]. Water lettuce, or *Pistia stratiotes*, is a perennial aquatic macrophyte that has attracted considerable interest because of its potential for wastewater treatment via phytoremediation. The numerous ecological and physiological characteristics of this plant make it particularly useful for eliminating different types of pollutants from aquatic environments. These characteristics were examined in the following synthesis, with particular attention paid to its growth characteristics, capacity to absorb heavy metals, and general efficacy in wastewater treatment. A view of *Pistia stratiotes* is shown in Figure 3.

Figure 3. *Pistia stratiotes* adopted from [35]

The ability of *Pistia stratiotes* to absorb heavy metals is one of its most remarkable ecological characteristics. This plant can dramatically lower the levels of heavy metals in contaminated water, including Pb, Zn, Cd, copper (Cu), and Cr. Likewise, research has demonstrated that *Pistia stratiotes* can efficiently bioaccumulate pollutants in its tissues, which makes it a promising choice for the phytoremediation of industrial and household wastewater [36]. This plant's large root system, which increases its contact with contaminants in water column, is thought to be responsible for its capacity to absorb heavy metals [37].

In addition to its capacity to absorb heavy metals, *Pistia stratiotes* is distinguished by a dense root system, which is essential for the effectiveness of its phytoremediation. The plant can float on the water's surface because its leaf surfaces are hydrophobic, which also makes it easier for pollutants to enter through its roots [32]. Additionally, the plant can quickly establish itself in nutrient-rich waters, which is often a feature of polluted environments, thanks to its rapid growth rate [38]. This rapid growth may result in significant biomass accumulation, which is advantageous for wastewater treatment. The physiological characteristics of *Pistia stratiotes* also increase its efficacy in treating wastewater. For the plant to grow and produce biomass, it must have a high net photosynthetic rate [36]. It can flourish in a range of environmental circumstances, such as different light intensities and nutrient levels, which complements its high photosynthetic activity [37].

*Pistia stratiotes* has been demonstrated to be especially effective in treating wastewater from a variety of sources, such as industrial effluents and aquaculture. For instance, research has shown that this plant can eliminate up to 95% of the phosphate content in wastewater, which helps with eutrophication [39]. Incorporating *Pistia stratiotes* into wastewater treatment systems improves the removal of pollutants and encourages the recovery of valuable resources, like biogas, from the biomass produced during treatment process [38]. The quick growth can help produce biomass, but it can also present problems, like the possibility of becoming invasive and outcompeting native species [40]. To balance the advantages of employing *Pistia stratiotes* for phytoremediation with the possible ecological risks associated with its proliferation, careful management is necessary.

*Pistia stratiotes* is a potent agent for wastewater treatment through phytoremediation because of its many ecological and physiological characteristics. It is a useful tool in the fight against water pollution because of its capacity to absorb heavy metals, its rapid growth, and its adaptability to different environmental conditions. The ecological effects of phytoremediation must be carefully evaluated to ensure that its advantages do not compromise ecological integrity. Subsequent investigations should concentrate on maximizing the application of *Pistia stratiotes* in wastewater treatment systems while tracking their ecological effects to support sustainable aquatic ecosystem management techniques.

### 3.4. *Typha* spp.

*Typha* spp., particularly *Typha latifolia* and *Typha angustifolia*, serve as effective phytoremediators in both tropical and temperate wetlands due to their ecological versatility and rapid growth rates. These species can thrive in diverse environmental conditions, including varying salinities, making them ideal for constructed wetlands designed to treat wastewater [41]. Their extensive root systems provide substantial surface area for microbial colonization, enhancing nutrient absorption and pollutant breakdown, and facilitating the bioaccumulation of harmful substances such as heavy metals [42].

However, the distribution of *Typha* spp. can significantly impact native biodiversity, as they may outcompete local flora, especially in restored wetlands [43]. The coexistence of native and invasive *Typha* species could alter habitat dynamics, necessitating careful management to enhance the ecological balance within these systems [43]. Current research highlights their utility in treating specific wastewater types, from breweries to tanneries, confirming *Typha* spp. as critical components in sustainable wastewater treatment strategies [44].

*Typha* species, especially *Typha latifolia* and *Typha angustifolia*, have attracted considerable attention in the wastewater treatment field because of their remarkable capacity to flourish in nutrient-rich and contaminated environments. These characteristics make them perfect candidates for use in constructed wetlands, which are engineered systems that use soil, plants, and microorganisms to treat different types of wastewaters naturally. The literature contains a wealth of information on the effectiveness of *Typha* species in eliminating pollutants, such as nitrogen, phosphorus, heavy metals, and organic compounds. A view of the *Typha* spp. is shown in Figure 4.

The extensive root systems of *Typha* species, which offer a significant surface area for microbial colonization, are one of their main ecological advantages. This root structure improves the microbial activity required for the breakdown of organic pollutants and facilitates nutrient absorption. Because it fosters a synergistic relationship that improves pollutant degradation 53, the interaction between plant roots and microbial communities is essential to the overall effectiveness of constructed wetlands [41].

Figure 4. *Typha* spp. adopted from [41]

*Typha* species have physiological characteristics that demonstrate high tolerance to a variety of contaminants, such as organic pollutants and heavy metals. *Typha* can effectively lower the concentrations of heavy metals in the surrounding environment by accumulating large amounts of CD and mercury from contaminated sediments, according to studies [45]. A crucial component of their function in phytoremediation is their capacity to bioaccumulate pollutants, which allows them to stabilize pollutants in their tissues and stop additional leaching into the environment, in addition to eliminating them from water [46].

*Typha* species are also useful for wastewater treatment applications because of their rapid growth rates and ability to adapt to different environmental conditions. Because they can flourish in both freshwater and brackish environments, constructed wetlands can be designed in a variety of ways, making them appropriate for a range of geographical locations and wastewater types [47]. Their resilience against environmental stressors, like salinity and fluctuating water levels, which are prevalent in many wastewater treatment scenarios, is also influenced by their adaptability [48]. In addition to removing pollutants, *Typha* species in artificial wetlands support the general ecological well-being of these systems. *Typha* species improve biodiversity in artificial wetlands by providing habitats for a variety of aquatic organisms, such as fish and invertebrates. By providing wildlife with a place to hide, their thick stands can support ecological balance [49].

A growing body of research demonstrating the efficacy of *Typha* spp. in a variety of settings supports their incorporation into wastewater treatment systems. For instance, research has demonstrated that *Typha* can efficiently treat wastewater from breweries, reducing nutrient concentrations significantly through microbial activity and phytoremediation. Their use in treating wastewater from tanneries has also shown similar efficacy, highlighting their adaptability as a treatment choice [50].

*Typha* species are extremely useful for wastewater treatment because of their ecological and physiological characteristics. They are important contributors to the creation of sustainable wastewater management plans because of their capacity to eliminate organic pollutants, heavy metals, and nutrients as well as their versatility and contribution to biodiversity enhancement. The potential of *Typha* spp. to aid in ecological restoration and environmental remediation will likely grow as research advances, opening the door for creative methods of handling contaminated water supplies.

### 3.5. Napier grass

Napier grass, also known as elephant grass, is a tropical perennial grass with notable ecological and physiological traits that make it suitable for various environmental applications, particularly in wastewater treatment. This grass can thrive in contaminated environments, effectively absorbing nutrients and heavy metals, which enhances both environmental recovery and biomass production for agricultural purposes [51], [52]. Native to Sub-Saharan Africa, Napier grass is well-adapted to diverse tropical conditions and demonstrates resilience to heat and water scarcity, making it suitable for regions susceptible to climatic stressors [53], [54].

Tropical perennial grass known as Napier grass (*Pennisetum purpureum*) has attracted a lot of interest because of its physiological and ecological characteristics, especially when it comes to wastewater treatment. Owing to its rapid growth, high biomass production, and ability to adapt to different environmental conditions, this grass species is a great choice for phytoremediation and artificial wetland systems that treat contaminated water. Napier grass's usefulness in wastewater treatment is largely due to its capacity to flourish in contaminated environments as well as its efficiency in absorbing nutrients and accumulating heavy metals. A view of Napier grass is depicted in Figure 5.

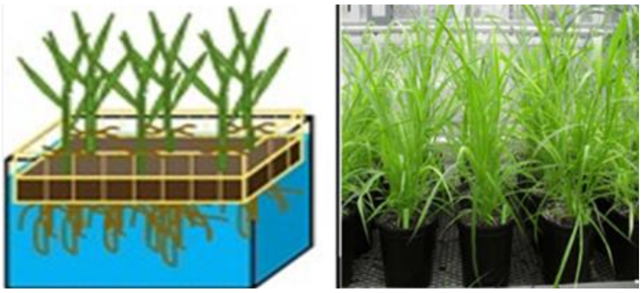

Figure 5. Napier grass adopted from [55]

Napier grass's high resilience and productivity are two of its main benefits when it comes to wastewater treatment. According to studies, hybrid Napier grass types, like Pakchong, grow remarkably quickly and efficiently use different forms of nitrogen, which is crucial for nutrient-rich wastewater applications [56]. Grasses thrive in conditions where other plants might suffer because of their resistance to high nutrient concentrations, especially those of nitrogen and phosphorus. It is crucial to remember that excessive phosphorus can have a detrimental effect on growth metrics, such as root length and chlorophyll content, which highlights the necessity of carefully controlling wastewater nutrient levels [56].

Napier grass is especially useful in phytoremediation attempts because it has also been found to be a hyperaccumulator of heavy metals. According to research, this grass can significantly reduce metal toxicity in aquatic systems by absorbing and accumulating heavy metals, such as Cr, from contaminated water. The mechanisms behind this hyperaccumulation include phytoextraction, in which the plant detoxifies the environment by absorbing metals through its roots and storing them in its tissues [57]. This characteristic not only improves the region's ecological well-being but also makes it possible to recover valuable metals from wastewater. Napier grass has ecological advantages beyond its capacity to absorb pollutants. In constructed wetlands, where soil integrity is essential for efficient water treatment, its vast root system helps stabilize the soil and reduce erosion [58].

The effectiveness of Napier grass in treating different types of wastewater in artificial wetland systems has been thoroughly investigated. For example, it has been shown to be effective in treating dairy wastewater, with reports showing notable decreases in pathogens and nutrient levels [59]. Grass can increase the overall effectiveness of these systems because it can flourish under the anaerobic conditions found in artificial wetlands. Additionally, research has demonstrated that Napier grass can raise the DO content of treated water, which is essential for preserving aquatic life.

Napier grass's physiological characteristics are also essential to its efficacy as a wastewater treatment facility. The grass's capacity to photosynthesize effectively, even in a variety of environmental circumstances, is linked to its high biomass production [60]. Furthermore, it has been demonstrated that adding arbuscular mycorrhizal fungi to Napier grass enhances both its growth and phytoremediation potential. These symbiotic connections improve the absorption of nutrients, especially phosphorus, which is frequently scarce in wastewater. Mycorrhizal fungi can greatly boost Napier grass's biomass and nutrient content, increasing the plant's overall efficacy in wastewater treatment systems [61].

Napier grass has economic benefits in addition to ecological ones. The application in wastewater treatment can lower the expenses related to traditional treatment techniques, which frequently call for large energy and chemical inputs [57]. Municipalities and agricultural operations can effectively treat wastewater and produce biomass for use as fodder or bioenergy feedstock by integrating Napier grass into artificial wetlands [62]. This two-fold advantage highlights the potential of Napier grass as an environment-friendly wastewater treatment method.

Because of its many ecological and physiological characteristics, Napier grass (*Pennisetum purpureum*) is an excellent option for treating wastewater. It is an essential component of constructed wetland systems because of its rapid growth, high biomass production, and capacity to absorb and store nutrients and heavy metals. By producing biomass for a variety of applications, the incorporation of Napier grass into wastewater management plans not only improves environmental sustainability but also yields financial gains. This adaptable grass's role in supporting ecological health and resource recovery is expected to grow as more research is conducted to fully understand its potential, which will lead to more environmentally friendly and sustainable farming methods.

Phytoremediation, the use of plants to remove or stabilize contaminants from the environment, presents a robust strategy for decentralized water treatment systems, promoting ecological health and sustainability. Key aquatic species such as *Eichhornia crassipes*, *Phragmites australis*, and *Typha* spp.

demonstrate remarkable capabilities to absorb heavy metals and nutrients, thereby enhancing water quality and supporting biodiversity. Furthermore, by integrating these plants into circular water systems, municipalities can not only improve wastewater treatment but also recover resources from biomass, thereby aligning with circular economy principles. Moreover, the resilience of these plants to varying environmental conditions renders them suitable for use in regions impacted by climate change. Their ability to dampen pollution loads while promoting ecological restoration aids in developing adaptive solutions to water quality challenges exacerbated by increasingly erratic climate patterns. This capacity for natural assimilation and stabilization of pollutants solidifies the role of phytoremediation in fostering climate-resilient and sustainable water management strategies, further highlighting its significance in modern environmental conservation efforts.

## 4. CONCLUSION

Numerous plant species, such as *Eichhornia crassipes, Phragmites australis, Pistia stratiotes, Typha* spp., and Napier grass have been examined and found to have significant potential for wastewater treatment and phytoremediation. Every species has distinct physiological and ecological characteristics that improve its capacity to absorb pollutants and restore its environment. *Phragmites australis* is excellent for microbial support and nutrient uptake in artificial wetlands, whereas *Eichhornia crassipes* is notable for its high capacity to absorb heavy metals and rapid growth. *Pistia stratiotes* exhibits exceptional sediment stabilization and heavy metal bioaccumulation, both of which enhance water quality. Similarly, *Typha* species are efficient at removing nutrients and providing habitat, whereas Napier grass produces a large amount of biomass and can adapt to different wastewater conditions. When combined, these species increase biodiversity and soil health in addition to improving water quality through pollutant remediation. However, to balance the risks and ecological benefits, the potential for invasiveness in non-native environments requires careful management. To ensure sustainable practices that support ecological integrity and resource recovery, future research should focus on optimizing the use of these plants in various wastewater treatment applications. Future research extensions could explore genetic enhancement to increase pollutant absorption efficiency and resilience. Additionally, investigating microbial symbiosis may yield synergistic effects that enhance the overall phytoremediation capacity of these species. Implementing AI-assisted species selection can optimize the process of choosing the most effective plant combinations for specific contaminants and environmental conditions, thereby improving treatment outcomes. Such integrative approaches promise to bolster the ecological benefits of these plants while mitigating risks associated with invasiveness and enhancing sustainability in wastewater management practices.

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## AUTHOR CONTRIBUTIONS STATEMENTS

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
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I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
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Vi : **Vi**sualization
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## CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest

## DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [SS], upon reasonable request.

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