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# Recent Progress of Phytoremediation-Based Technologies for Industrial Wastewater Treatment

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## ABSTRACT

Phytoremediation is considered of a cost effective and environmentally friendly technology and has been used successfully for the remediation of soils and water contaminated with various pollutants. Specifically for full scale application to treat industrial wastewater, phytoremediation is used as sole technology for different types of wetlands. However, phytoremediation of polluted water in wetland type reactor has been mostly studied as black box. The method to measure the performance is only based on pollutant removal efficiency and there is very limited information available about of the pollutant removal mechanisms and process dynamics in these systems. Thus, the aim of this chapter was to briefly review basic processes of phytoremediation, its mechanisms and parameters, and its interaction between rhizo-remediation and microbe-plant. In addition, this chapter also elaborated phytoremediation challenges and strategies for full-scale application, its techniques to remove both organic and inorganic contaminants by aquatic plants in water, and some examples of applications in industries.

**Keywords:** aquatic plants; constructed wetlands; environmental pollution; industrial wastewater; phytoremediation.

## INTRODUCTION

Conventional wastewater treatment is not completely effective method for water contaminants removal. Trace concentrations of toxic contaminants can still be found in wastewater effluent. Thus, an alternative technology to reduce the contaminant concentration to the safe level is necessary. Different types of wastewater treatment technology are introduced. However, most of these technologies are considered to have high energy requirement, high carbon emission, excess sludge discharge and high maintenance cost (Mustafa and Hayder, 2020). A sustainable management of aquatic ecosystem needs eco-friendly and low-cost remediation methods. Aquatic plants have the potential to remove inorganic and organic pollutant. Phytoremediation is defined as a bioremediation that utilizes plants for wastewater remediation and utilizes plants roof to adsorb nutrients in the wastewater. Specific species of plants even have the ability to accumulate certain pollutants. Phytoremediation has been proven to be more efficient, cost effective and more environmentally friendly than conventional treatment.

There are the plants that have high phytoremediation ability, such as *Brassica juncea, Arundo dona*x L. *Miscanthus* sp., *Typha latifolia* and *Thelypteris palustris* for heavy metals removal such as Zn and Cu, by using bioaccumulation mechanism (Ullah et al., 2015). *Salvinia molesta* and *Pistia stratiotes* also have been widely used for the treatment of agricultural, domestic and industrial wastewater (Mustafa and Hayder, 2020). Type of plants is not only the main factor for successful phytoremediation process, the role of rhizosphere-associated microorganisms is also important. Microorganisms help improving phytoremediation process through biosorption and bio-augmentation. Organisms such as *Acidovorax, Alcaligenes, Bacillus 95 mycobacterium, Paenibacillus, Pseudomonas*, and *Rhodococcus* have been reported to enhance the phytoremediation process (Sharma et al., 2021).

However, phytoremediation of polluted water in wetland type reactor has mostly been studied as black box. The method to measure the performance is only based on pollutant removal efficiency and there is very limited information available about of the pollutant removal mechanisms and process dynamics in these systems. This chapter briefly reviews basic processes of phytoremediation, its mechanisms and parameters, and its interaction between rhizo-remediation and microbe-plant. In addition, it also elaborates the phytoremediation challenges and strategies for full-scale application, its techniques to remove both organic and inorganic contaminants by aquatic plants in water, and some examples of applications in industries.

## PRINCIPLES OF PHYTOREMEDIATION

The concept of phytoremediation must be differentiated from bioremediation. Bioremediation process is merely assisted by heterotrophic bacteria that are responsible for organic contaminants degradation and mineralization, as well as accumulation of metals and other elements and oxidation of inorganic compounds (McCutcheon and Jørgensen, 2018). In turn, phytoremediation process is based on the role of photoautotroph bacteria to treat contaminants via mechanisms such as:

- Release organic matter as their metabolism products (during growth and maintenance), thus improves the number of heterotrophs bacteria.
- Pump the oxygen into the plant root zone and also deposit secondary metabolites during root die-back in the rhizosphere to boost the number of aerobic, facultative, or anaerobic organisms to degrade or accumulate contaminants
- Transport pollutants into active microbial zones by evapotranspiration, blockage of flows, or other means.

In more detail, phytoremediation mechanisms can be broken down into several types, namely: phytodegradation, phytoextraction, phytovolatilization, phytofiltration and phytostabilization, which is shown in Table 1.

## INTERACTION BETWEEN RHIZO-REMEDIATION AND MICROBE-PLANT IN PHYTOREMEDIATION

Rhizosphere is the most important area during phytoremediation (Purwanti et al., 2020). Rhizosphere is the place where pollutants have contact with the treatment agent (plant) (Al-Ajalin et al., 2020a; Ismail et al., 2020). Plants root played an important role in the removal of pollutant from wastewater (Al-Ajalin et al., 2020b). Beside the root, there are also microbes (known as rhizobacteria) that also greatly support the degradation of pollutant in the rhizophore (Jehawi et al., 2020). Plant roots and microbes interact, which leads to the removal of contaminants from the contaminated medium as illustrated in Figure 1.

There are 4 major interactions in rhizosphere occurred during the phytoremediation of pollutants from wastewater: phytostimulation (Hawrot-Paw et al., 2019), rhizofiltration (Rahman and Hasegawa, 2011), rhizodegradation (Imron et al., 2019b; Kadir et al., 2020), and phytostabilization (Bolan et al., 2011). Phytostimulation is a process in which plant releases its exudates in the rhizosphere (Backer et al., 2018). The released exudates nearby the root area provide good environment for rhizobacteria to grow optimally (Abdullah et al., 2020). The release of exudates stimulates the growth of rhizobacteria which the perform symbiotic interactions (Shahid et al., 2020). The phytostimulation cannot be separated from rhizodegradation. Rhizodegradation is

**Table 1.** Types of phytoremediation mechanisms, their affecting factors and applications

| Type of phytoremediation | Mechanisms | Affecting factors | Applications | Reference |
|---|---|---|---|---|
| Phytodegradation/ phyto-oxidation | Phytodegradation occurs when aquatic and terrestrial plants take up, store, and biochemically degrade or transform organic compounds to harmless by-products, products used to create new plant biomass, or by- products that are further broken down by microbes and other processes to less harmful compounds. Growth and senescence enzymes, sometimes in series, are involved in plant metabolism or detoxification. Reductive and different parts of the plant. | Concentration and composition of pollutant, plant species, and soil conditions. | Soil, sediment sludges, groundwater and surface water, wetlands, wastewaters, and air contaminated with compounds | (Kagalkar et al. 2011; Park et al. 2011) |
| Phytoextraction | Contaminants is transferred to harvestable plant tissues by Hyperaccumulation | Contaminants concentration, the depth of the contamination in the soil, the possibility of leach of pollutants into ground water | Soil | (Wang et al. 2020) |
| Phytovolatilisation | Volatilisation by leaves . Transformation of toxic substances into less toxic. | The possibility of re-deposition of pollutant back into ecosystem by precipitation (elemental | Soils, sediments, sludges, wetlands, and groundwater up | (Epa 2019) |
| Phytofiltration | Accumulation of contaminants in rhizosphere | The plant must have high Metal-resistant, high adsorption surface, high tolerance of hypoxia. Long-term maintenance depends on type of contaminant and depth, hinders plant growth, highly species specific | Wetlands, wastewater, landfill leachates, and groundwater contaminated with metals, radionuclides, organic chemicals, nitrate, ammonium, phosphate, and pathogens | (Sandhi et al. 2018) |
| Phytostabilization | Revegetation to prevent erosion and sorbed pollutant transport | Plants control pH, soil gases, and redox that cause speciation, precipitation, and sorption to form stable mineral deposits (effects ecosystem succession unknown on long-term stability and thus sustainability) | Soil, mine tailings, wetlands, and leachate pond sediments contaminated with metals, phenols, anilines, and some pesticides | (Kurniawan et al. 2022) |

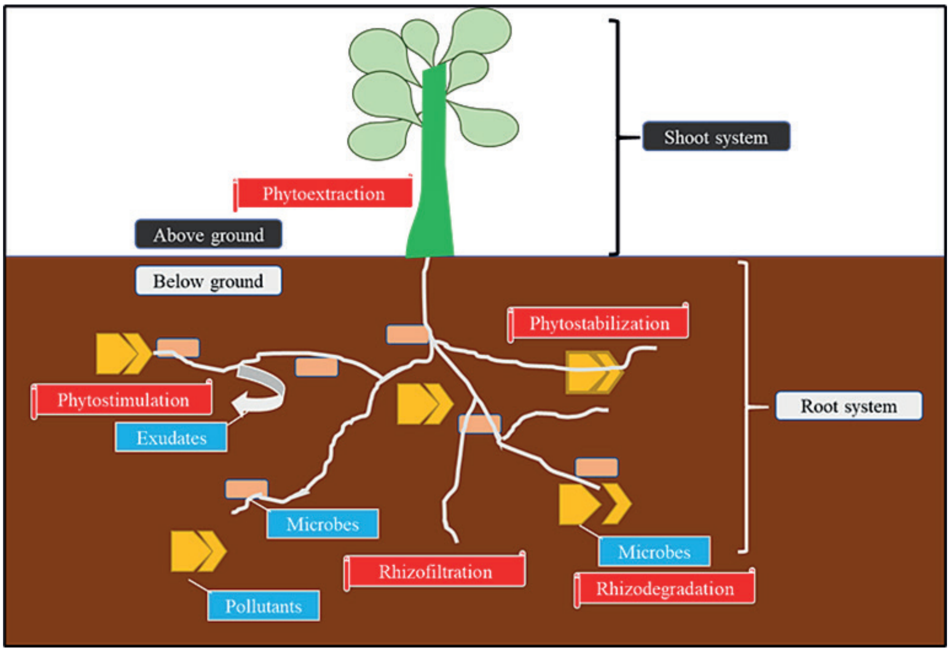


**Figure 1.** Microbe-plants interaction during phytoremediation

the mechanism where rhizobacteria perform the degradation of pollutants in rhizosphere (Almansoory et al., 2021; Imron et al., 2020). The better the growth of rhizobacteria, the more degradation of pollutants will be obtained. Rhizodegradation mostly occurred during the treatment of organic materials-rich wastewater (Tangahu et al., 2019).

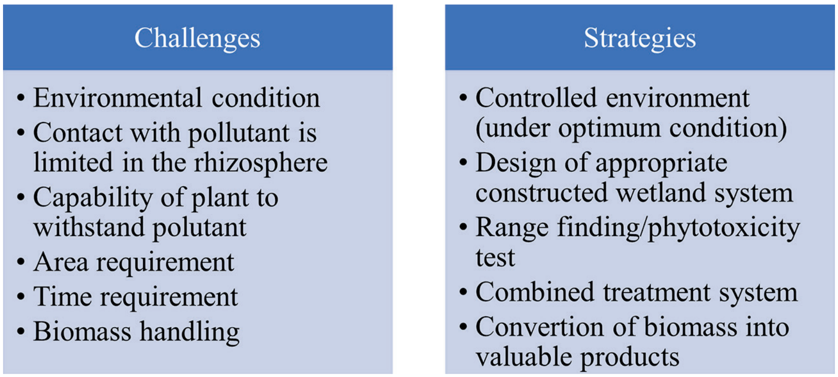
For the wastewater containing heavy metals, rhizobacteria may act as stabilization agent that transforms the ionic state metals into stable state (Imron et al., 2019a; Kurniawan et al., 2018; Titah et al., 2018). Rhizobacteria may also perform bioaccumulation, which then leads to the stabilization of heavy metals inside cells (Purwanti et al., 2019a; Titah et al., 2019). In addition to the rhizobacterial processing heavy metals, plant exudates contain complex compound that may increase the solubility of metals (to be treated further by rhizobacteria) or to bind directly with heavy metals to produce complex metal-exudates which then stabilized in the rhizosphere (phytostabilization) (Dakora and Phillips, 2002). Plant roots also perform physical treatment of wastewater by performing screening of bulk compounds in their roots. This mechanism mostly occurred in the treatment of pollutants using fibrous root type species (Elias et al., 2014). After performing several mechanisms in rhizosphere, a plant then performs phytoextraction in which it absorbs pollutants via transfer mechanism to bioconcentrate it into its cell (Purwanti et al., 2020). Phytoextraction can occur directly to pollutant and also its intermediate compounds (after degraded by rhizobacteria). There are no significant difference mechanisms between the treatments of wastewater using sub-surface or free-surface constructed wetland. The major differences are the species used and the contaminated medium that need to be treated (Kadir et al., 2020; Purwanti et al., 2018b, 2018a).

## RHIZO-REMEDIATION AND MICROBE-PLANT INTERACTION IN PHYTOREMEDIATION

Despite many advantages of phytoremediation application for industrial wastewater treatment, this method still has some challenges to be faced during application. Some challenges of phytoremediation application and strategies that may cover the challenges are summarized in Figure 2.

Phytoremediation needs certain conditions to work well, including the requirement of sunlight (Miranda et al., 2020), specific nutrient for plant growth (Bansal et al., 2019; Varma et al., 2021), temperature (Mao et al., 2015), humidity (Armstrong et al., 1992), etc. These requirements need to be fulfilled during application to obtain the best removal performance. Phytoremediation is considered to be very suitable for use in tropical countries (Ahmad et al., 2017) due to the availability of sunlight throughout the year and optimum temperature and humidity for plant growth, while in sub-tropical countries, controlled environment is highly needed (Ismail et al., 2019). Greenhouse treatment is suggested to be applied to maintain the optimum environmental conditions for plants to treat pollutants. Under controlled environment, plants will be able to maintain their performance throughout the year that may lead to the desired removal efficiencies.

Rhizosphere is the most important area in phytoremediation since the contact of pollutants and treatment agents occurs there (Kamaruzzaman et al., 2019). This may become a challenge when plants root do not have a good contact with pollutants. To overcome this issue, the design of appropriate constructed wetland needs to be conducted prior to the application



Challenges

- Environmental condition
- Contact with pollutant is limited in the rhizosphere
- Capability of plant to withstand polutant
- Area requirement
- Time requirement
- Biomass handling

Strategies

- Controlled environment (under optimum condition)
- Design of appropriate constructed wetland system
- Range finding/phytotoxicity test
- Combined treatment system
- Convertion of biomass into valuable products

**Figure 2.** Challenges and strategies of phytoremediation application

(Purwanti et al., 2018b). In designing appropriate constructed wetland, several major criteria need to be considered: characteristic of pollutants (Mostafa, 2015; Sharuddin et al., 2018), fate of pollutants (Logeshwaran et al., 2018), type of wetland that will be used (Al-Ajalin et al., 2020c), type of plants, plants growth (related to the root growth and penetration in medium) (Schwammberger et al., 2019), medium for plants (Sun et al., 2007), and depth of constructed wetland (Al-Ajalin et al., 2020a).

By using biological method, researchers need to aware that certain concentration of pollutants may disturb the performance of phytoremediation. Only certain plants that can survive high loading of pollutant may perform a better removal in treatment (Kwoczynski and Čmelík, 2021). There is a limit of pollutant concentration that can be tolerated by plants (Abdullah et al., 2020). To avoid the death of plants, which may lead to the decreasing of removal performance, selection of plant species and range finding/phytotoxicity test need to be conducted prior to the application of phytoremediation (Purwanti et al., 2018a; 2019). Several criteria in the selection of plant species to be used include its capability to withstand high pollutant load (Abdullah et al., 2020), the removal performance (Kurniawan et al., 2020), and capability to growth (perennial plants are more preferable) (Al-Baldawi et al., 2015). The range finding/phytotoxicity test needs to be performed to obtain the maximum concentration of pollutant that can be treated by the utilized species. If plants can withstand 100% concentration of pollutant, then the plants can be used as primary treatment technology. Secondary or tertiary treatment option should be chosen if a plant can only withstand lower concentration of pollutants.

Application of phytoremediation to treat industrial wastewater requires large area and is also considered to be time consuming (Abdullah et al., 2020). These issues are highly related with the rate of pollutants degradation by plants during treatment. Biological treatment has different reaction as compared to chemical treatment (Imron et al., 2020). In chemical treatment, stoichiometry of reaction controls the degradation of pollutant based on the equilibrium of reactants and products (Kis et al., 2017). In biological treatment, the capability of plants cannot be simply calculated as reactants and products equilibrium due to the complex mechanisms that involve many factors occurring during treatment (Karpowicz et al., 2020; Nottingham et al., 2018). To overcome these issues, most researchers suggest the utilization of phytoremediation technique as secondary or tertiary treatment to purify wastewater before discharge into water bodies. Chemical treatment is suggested as primary treatment, which may reduce the pollutant load in phytoremediation stage that may produce better removal rate, reducing the required time and surface area for treatment.

As plant grows during the treatment, plant biomass is produced, and its amount can be considered as abundant. If phytoremediation was applied to treat toxic substances (commonly heavy metals), the produced plant biomass needs to be handled following the standard procedure of handling toxic substances (Kwoczynski and Čmelík, 2021). If phytoremediation was applied to treat organic-rich or nutrient-rich wastewater, several conversion possibilities can be selected. Several biomass utilization studies had been successfully applied to convert biomass into animal feed (Kadir et al., 2020), biochar (Das et al., 2021), adsorbent (Alshekhli et al., 2020), biofuel (Correa et al., 2019; Rezania et al., 2020), and even fertilizer (Diacono et al., 2019; Kurniawan et al., 2020). With these conversion options, the wastewater treatment using phytoremediation may lead to the cleaner production strategy from utilization of treatment by-product.

## PHYTOREMEDIATION TECHNIQUES BY AQUATIC PLANTS FOR BOTH ORGANIC AND INORGANIC CONTAMINANTS REMOVAL IN WATER

### Aquatic plants selection

Aquatic plants are required in phytoremediation for degrading and removing contaminants within aquatic environments. These plants include ferns, pteridophytes, and freshwater adapted angiosperms. Aquatic plants are preferable to terrestrial plants for wastewater treatment because of their faster growth rate, larger biomass production, and better contaminant removal ability due to direct contact with the wastewater. The effectiveness of these plants in phytoremediation can be assessed by estimating the contaminants removed from the target area. Not only for remediation purposes, many of such aquatic plants also serve as bioindicators and biomonitors (Rai, 2009).

In addition, some keys principles that need to be considered in operating a phytoremediation system are as follows: a) identifying the suitable and efficient aquatic plants for the phytoremediation system; b) uptake of dissolved nutrients (e.g. N, P, and metals) by the aquatic plants; and c) harvesting process and utilization of the plant biomass generated from the phytoremediation system (Lu et al., 2010). Regular harvest of the aquatic plant biomass from a remediation site is necessary. Otherwise, the plants' biomass will be decomposed and subsequently release the stored contaminants back to the aquatic environment (Kumwimba et al., 2020).

Selection of aquatic plants that can grow well while degrading targeted contaminants is critical. Some plants commonly used for phytoremediation could experience disrupted growth if exposed to a high level of contaminants. The toxicity effects of the contaminants against aquatic plants are varied. Some negative responses of aquatic plants toward aquatic contaminants are growth reduction, wilting, chlorosis, reduction of roots and shoots length or volume, chlorophyll reduction, reduction in photosynthetic activity, and plant mortality (Ansari et al., 2020). For instance, in the case of water hyacinth, the exposure to high levels of cadmium and zinc to (*Eichornia crassipes*) resulted in reduced growth, as determined from biomass production, survival rate, and crown root number (Sricoth et al., 2018b). Another study by de Campos et al. (2019) that exposed water lettuce (*Pistia stratiotes*) with a high level of arsenite showed that although *P. stratiotes* was able to maintain its biomass, there had been a significant reduction in the root volume, chlorosis in the leaves, and damage in the cell membranes.

The ability of aquatic plants to reduce contaminants varies between plants. Therefore, to reduce the unfavourable effects on the plants' growth in a phytoremediation system, it is necessary to pay attention to the characteristics of the selected plants. The ideal characteristics of aquatic plants used for phytoremediators are as follows: high growth rate, production of more above-ground biomass, widely distributed and highly branched root system, high bioaccumulation potential, ability to transform or degrade contaminants, ability to regulate chemical speciation, capacity to treat both organic and inorganic contaminants, high accumulation of the target heavy metals from soil (bioconcentration factor > 1), translocation of the accumulated heavy metals from roots to shoots (translocation factor > 1), tolerance to the toxic effects of the target heavy metals, good adaptation to prevailing environmental and climatic condition, resistance to pathogens and pests, easy cultivation and harvest, and repulsion to herbivores to avoid food chain contamination (Dhir, 2013 and Thampatti et al., 2020).

Another primary factor that needs to be considered in the utilization of aquatic plants in a phytoremediation system corresponds to understanding the characteristics of the wastewater to be treated. Wastewater is a mixture of pure water with a large number of chemicals (including organic and inorganic chemicals) and heavy metals produced from domestic, agriculture, industrial and commercial activities. Organic contaminants can be categorized into persistent organic pollutants (POP)/xenobiotics (i.e., dioxins, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls), pesticides (i.e., glyphosate, hexachlorocyclohexane, fenhexamid, and deltamethrin), and pharmaceutical and personal care products (PPCPs) (i.e., antibiotics, hormones, and pain relief medication) (Al Falahi et al., 2022). Meanwhile, primary inorganic contaminants are nutrients (i.e., N, P, and K) and metalloid elements (i.e., Fe, Al, Pb, Ni, Cd, and Cu). The existence of these various pollutants in the environment needs serious attention, since they can cause various harmful effects (Rahim et al., 2022). Potential adverse effects of those contaminants on the surrounding environment and living things are as follows: eutrophication, chronic toxicity, endocrine disruption, and antibiotic resistance (Fletcher et al., 2020).

## Types of aquatic plants

Aquatic plants have earned an immense reputation due to its capacity to clean up contaminated water bodies. With their extensive roots system, these plants become the best option for degrading contaminants in a phytoremediation system. On the basis of their growth form, aquatic plants can be classified into free-floating, submerged, and emergent plants (Al Falahi et al., 2022).

Free-floating aquatic plants are the plants with floating leaves and submerged roots. Several free-floating aquatic plants have been studied extensively and approved to be applied in different phytoremediation systems. Some recognized free-floating aquatic plants are duckweeds (*Lemna*, *Spirodela*, and *Wolffia*), water hyacinth

(*Eichhornia*), water ferns (*Salvinia*, *Azolla*), and water lettuce (*Pistia*). Those plants are known for having the capability to remove a wide variety of inorganic and organic contaminants, heavy metals, pesticides, and nutrients from various sources, such as industrial and domestic wastewater, sewage, and agricultural runoff. Moreover, those plants can grow in polluted sites with tremendous variation in temperature, pH, and nutrient level (Javed et al., 2019 and Ali et al., 2020).

Submerged aquatic plants are the plants that usually grow underwater and are rooted in mud. Their leaves are the main part for contaminants uptake. Some famous submerged plants that have been studied are watermilfoil (*Myriophyllum*), coontail or hornwort (*Ceratophyllum demersum*), pondweed (*Potamogeton*), Esthwaite waterweed (*Hydrilla*), and water mint (*Mentha aquatica*). Most of these plants are commonly found in slow-moving streams, ponds and lakes. Additionally, the effectiveness of these plants in removing contaminants depends on different factors such as contaminant types and their concentration, pH and temperature (Dhir, 2013 and Javed et al., 2019).

Emergent aquatic plants are plants usually found on submerged soil where the water table is 0.5 m below the soil. These plants grow their shoots and leaves above the water, while keeping

**Table 2.** Recent phytoremediation studies using some well-known aquatic plants

| Plant species | Life form | Target contaminant | Removal efficiencies | Reference |
|---|---|---|---|---|
| Common duckweed (*Lemna minor*) | Free-floating | Methylene Blue Dye | 80.56% | (Imron et al., 2019) |
| Least duckweed (*Lemna minuta*) | Free-floating | Cr (VI) and phenol | 75-85% for Cr (VI) and 100% for phenol | (Paisio et al., 2018) |
| Giant duckweed (*Spirodela polyrhiza*) | Free-floating | Antibiotic ofloxacin | 93.73–98.36% | (Singh et al., 2019) |
| | | Pb | 82.23-93.19% | (Goswami et al., 2018) |
| Water hyacinth (*Eichhornia crassipes*) | Free-floating | Ammonium nitrogen ($NH_4^+$-N) and dissolved organic nitrogen (DON) | >99% for both $NH_4^+$-N and DON | (Qin et al., 2020) |
| | | Cr (III) | 96.70% | (Gemeda et al., 2018) |
| Water lettuce (*Pistia stratiotes*) | Free-floating | COD, $NH_4^+$-N, nitrates, phosphates | 47.82-88.00% for COD, 76.78-98.79% for $NH_4^+$-N, 16.92-97.14% for nitrates, and 73.72-92.89% for phosphates | (Olguín et al., 2017) |
| | | Herbicide clomazone | 90% | (Escoto et al., 2019) |
| Water milfoil (*Myriophyllum aquaticum*) | Submerged | Total phosphorus | 78.2–89.8% | (Luo et al., 2017) |
| Spiked water milfoil (*Myriophyllum spicatum*) | Submerged | Zinc oxide | 29.5-70.3% | (Ergönül et al., 2020) |
| | | Cobalt and Caesium | 90% for Co and 60% for Cs | (Saleh et al., 2020) |
| Water thyme (*Hydrilla verticillate*) | Submerged | BOD, COD, and Suspended Solid (SS) | 66.72% for BOD, 77.78% for COD, and 55.55% for SS | (Jamil et al., 2019) |
| | | Phenol | 90-99% | (Chang et al., 2020) |
| Cattail (*Typha latifolia*) | Emerged | Hg, As, Pb, Cu and Zn | >80% for all metals, except for Pb 64% | (Anning & Akoto, 2018) |
| Bog bulrush (*Scirpus mucronatus*) | Emerged | Total Petroleum Hydrocarbon | 74.9-82.1% | (Almansoory et al., 2020) |
| Giant bulrush (*Scirpus grossus*) | Emerged | COD, color, and SS | 66.1% for COD, 55.8% for color and 87.2% for SS | (Yusoff et al., 2019) |
| | | TSS, COD, and BOD | 98% for TSS, 88% for COD and 93% for BOD | (Nash et al., 2020) |
| Soft stem bulrush (*Scirpus validus*) | Emerged | Decabromodiphenyl ether (BDE-209, C12OBr10) | 72.22-92.84% | (Zhao et al., 2017) |
| Common reed (*Phragmites australis*) | Emerged | Pharmaceuticals bezafibrate and paroxetine | 47-75% for bezafibrate and 65-95% for paroxetine | (Dias et al., 2020) |
| | | Cadmium, lead, and nickel | 93% for Cd, 95% for Pb, and 84% for Ni | (Bello et al., 2018) |

their roots beneath the surface. Cattails (*Typha*), bulrush (*Scirpus*), common reed (*Phragmites australis*), reed canary grass (*Phalaris arundinacea*), and foxtail flats edge (*Cyperus alopecuroides*) are well-known emergent aquatic plants that can effectively be used for phytoremediation (Ali et al., 2020). Emergent plants species have received considerable attention in nutrient phytoremediation and are often deployed in constructed wetlands, because they are relatively easier to harvest (Fletcher et al., 2020).

Furthermore, another type of plants that becomes a new interest in phytoremediation corresponds to transgenic plants. Transgenic plants were engineered so that specific genes in the plants can increase its metabolism and enhance detoxification process of organic pollutants for more effective phytoremediation. In this approach, incorporated genes secrete enzymes which degrade organic pollutants in the rhizosphere zone. This might solve the problem in plant harvesting and handling loaded with toxic metals, as all the metal detoxification and removal process occur in the rhizosphere by roots. Engineered *Arabidopsis thaliana* and *Nicotiana tabaccum* are examples of transgenic plants that are effective for removing heavy metals, cadmium, and mercury (Tiwari and Sarangi, 2019 and Ali et al., 2020).

Different species of aquatic plants have been long studied for its potential in phytoremediation with notable successes. Table 2 presents some common aquatic plants used in phytoremediation studies in recent years. However, it should be noted that contaminants degradation efficiencies depend on various interconnected factors; the factors include duration of exposure, contaminant's concentration, physicochemical properties of pollutants (e.g., solubility, pressure etc.), plants characteristics (e.g., species, root system etc.), and environmental characteristics (e.g., pH, temperature etc.) (Anand et al., 2017).

There have been extensive works on the application of aquatic plants in phytoremediation that focus on the ability of individual species. Meanwhile, the studies that explore the ability of mixed plant species to degrade contaminants are limited. Several studies that emphasize using plant communities have shown that species richness had a positive effect on removal of both single and multiple contaminants, such as total phosphorus (Geng et al., 2017), BOD and metals (Pb, Cd, and Zn) (Sricoth et al., 2018a), and total inorganic nitrogen (Geng et al., 2019).

However, competition between plants should be understood as this may impact the effectiveness of contaminants removal. Moreover, a study by Geng et al. (2017) also suggests that the composition of appropriate plants species might be more important than increasing species richness. Therefore, further studies to find optimal plant combinations for removal of particular contaminants are required, as this would help optimize phytoremediation efficiency.

## INDUSTRIAL WASTEWATER TREATMENT USING CONSTRUCTED WETLAND

Constructed wetland is the most used phytoremediation model which follows the basic principle of phytoremediation. Constructed wetland (CW) is divided into two basic principles, free water surface flow constructed wetland (FWSCW) and sub-surface flow constructed wetland (SSFCW). Subsurface flow is divided into vertical flow (VF) CW, horizontal flow (HF) CW, free vertical flow (FVF) CW and hybrid type CW (AL Falahi et al., 2022; Parde et al., 2020). Constructed wetland can remove high number of organic pollutants, especially nutrients, such as nitrogen and phosphorus. In integrated system of wastewater treatment plant, constructed wetland

**Table 3.** Industrial wastewater treatment using constructed wetland

| Industry | Wastewater | Treatment | Type of CW | Plant | OLR | HLR (cm d$^{-1}$) | HRT (days) | Removal (%) | Year | Country | Note |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Glass industry | Wastewater from washing glass sheets and the factory's machines production. | Settling tank-CW | HSFCW | Pampas grass | - | - | 6.8 | BOD$_5$: 90<br>COD: 90<br>TSS: 99<br>TN: 95<br>TP: 96 | 2018 | Iran | Full scale capacity 10 m$^3$/day |
| Tannery Industry | - | - | HSSFCW | *Canna indica*, *T. latifolia*, *P. australis*, *Stenotaphrum secundatum* and *I. pseudacorus* | COD: 332–1602 kg ha$^{-1}$d$^{-1}$<br>BOD$_5$: 218–780 kg ha$^{-1}$d$^{-1}$ | 3 & 6 | | COD: 41–73<br>BOD$_5$: 41–58 | - | Portugal | Five parallel pilot units<br>Surface area: 1.2 m$^2$<br>Depth: 0.60 m |

**Table 3. Cont.** Industrial wastewater treatment using constructed wetland

| Industry | Wastewater | Treatment | Type of CW | Plant | OLR | HLR (cm $d^{-1}$) | HRT (days) | Removal (%) | Year | Country | Note |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tannery Industry | - | Chemical-physical-CW | HSFCW (2 stages) | *Phragmites australis, Typha latifolia* | COD: 242-1925 kg $ha^{-1}d^{-1}$ and BOD: 126-900 kg $ha^{-1}d^{-1}$ | 6 | 2.5 & 7 | $BOD_5$: 88<br>COD: 92 | 2005-2006 | Portugal | Onsite<br>2 pilot units.<br>Surface area: 1.2 $m^2$, depth: 0.60 m |
| Sugar industry | Molases after Anaerobic | Anaerobic pond-CW | SFCW | *Cyperus involucratus, Typha augustifolia* and *Thalia dealbata* | $BOD_5$: 612 $kgha^{-1}$ $day^{-1}$ | - | - | SS: 90–93<br>$BOD_5$: 88–89<br>COD: 67<br>Total phosphorus: 70–76<br>$N\text{-}NH_4^+$: 77-82%,<br>$NO_3^-$: 94–95<br>Molasses pigment: 72–77 | 2007 | Thailand | Lab<br>0.6x2x0.5 m |
| Winery industry | - | Anaerobic treatment-CW | HSFCW | *Typha latifolia, Phragmites australis, Elodea canadensis, Ceratophyllum demersum, Nymphaea alba* and *Nymphaea rustica* | - |  | - | $BOD_5$: 92-98<br>COD: 87-98<br>TSS: 70-90<br>Total nitrogen: 50-90<br>Total phosphorus: 20-60 | 2001 | Italy | Onsite in 3 places: Casa Vinicola Luigi Cecchi & Sons (Siena); Azienda Vitivinicola "Tenuta dell'Ornellaia" (Leghorn); Azienda Agricola La Croce (Siena) |
| Winery industry | wastewater from the winery mixed with the sewage | A pre-treatment (coarse screening-Imhoff tank -equalization tank ) – multistage | VSSFCW (140 $m^2$) - HSSFCW (60 $m^2$) and FSFCW (30 $m^2$) | *Phragmites australis L., Cyperus Papyrus var. Siculus, Canna indica L., Scirpus lacustris L., Nymphaea alba L., Iris pseudacorus L.* | - | - | 110 h | Removal of about 69% for TSS, 78% for COD, and 81% for $BOD_5$ | March 2014 to June 2018 | Sicily (Italy) | multistage pilot CW system |
| Dairy industry | Reject water from dewatering aerobic sludge | Retention tank-CW | SSVFCW | *Phragmites australis* | BOD 13.2 g. $m^{-2}$ $d^{-1}$, $N\text{-}NH_4^+$ 2.6 $g.m^{-2}d^{-1}$ | - | - | $BOD_5$: 88.1–90.5%,<br>TKN: 82.4–76.5%,<br>$N\text{-}NH_4^+$: 89.2–85.7%,<br>TP: 30.2–40.6% | 2012 | Poland | Pilot scale<br>2 bed parallel<br>10 $m^2$ x 0.65 m depth<br>5 $m^2$ x 1m depth |
| Olive mill industry | Effluent from extraction process | Trickling filter - CW | VFCW | *Phragmites australis* | COD 88 – 6589 $gm^{-2}d^{-1}$; phenols 17 - 997 $gm^{-2}d^{-1}$; TKN 3.0-175 $gm^{-2}d^{-1}$; OP 3.0 - 20.0 $gm^{-2}d^{-1}$, | - | - | Removals of about 70%, 70%, 75% and 87% for COD, phenols, TKN and ortho-phosphate | 2010 | Greece | Pilot scale of two series, each 4 units<br>Dimensions were 96x38.5x31 cm in depth |
| Metallurgic industry | Effluent from production plus sewage | Primary treatment -CW | FWS CW | *E. crassipes, T. domingensis* and *P. cordata* | - | - | 7 – 12 days | Cr: 86<br>Ni: 67<br>Fe: 95<br>Nitrate: 70<br>Nitrite: 60 | 2002-2004 | Santo Tom´e (Argentina) | 50 m length<br>40 m wide<br>0.5–0.8 m deep |
| Mining industry (Gold mining) | Effluents from the mining (Hg: 0.11 ± 0.03 μg $mL^{-1}$) and spiked with $HgNO_3$ (1.50 ± 0.09 μg $mL^{-1}$) | Tank - CW | HSSFCW | *Limnocharis flava* | - | - | 5 days | Hg: 90 | 2016 | Colombia | Lab pilot scale, four trays of 50x20x20 cm |
| Oil well | produced waters from oil fields (i.e., waters that have been in contact with oil in situ) | RO-CW | HSSFCW | *Typha latifolia*<br>*Scirpus californicus* | - | - | 5 days | CW decrease water soluble toxic fraction that suitable for irrigation | 2000 | South Carolina, US | Lab pilot scale<br>4 units of 0.19 $m^2$ x 0.28 m |
| Industrial estate | Industrial wastewater (textile, chemicals, ghee and cooking oil, marble, steel, plastic, soap and detergent industries) | FSF-CW<br>Free surface flow wetland | CW | *T. latifolia, P. stratiotes, P. australis, C. aquatilis* and *A. plantago-aquatica* | - | - | 40 h | Pb: 50<br>Cd: 91.9<br>Fe: 74.1<br>Ni: 40.9<br>Cr: 89<br>Cu: 48.3 | 2003–2004. | Gadoon Amazai Industrial Estate (GAIE), Swabi, Pakistan | 7 cells CWs with a total area of 4145.71 $m^2$, total capacity of 1305.58 $m^3$ |

could be placed after biological secondary treatment (i.e., activated sludge system) to enhance the quality of the effluent. Table 3 reviews full scale constructed wetland application in industries.

## CONCLUSIONS

Phytoremediation is one of the oldest techniques to remove pollutants from the environment, particularly in water and soil. The basic principle of phytoremediation is using the interaction between plant roots and root microorganisms. Deep knowledge about microbe-root plant interaction mechanisms is required to develop a more robust, effective and efficient model. Constructed wetland is the most used phytoremediation model. This model has a great potential in the future due to its robustness and flexibility. Nowadays, many advance technologies, such as Microbial Fuel Cell (MFC), could be integrated in the constructed wetland system. The possibility of system integration between phytoremediation and another advance technology should be explored extensively to enhance the effluent quality and reduce the cost.

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