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REVIEW ARTICLE

Pollutant removal through phytoremediation: a review

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Abstract
Pollution is a serious problem faced by Indonesia, where many water sources are contaminated by domestic, industrial and agricultural waste. These sources of pollution include fecal waste, household waste, and hazardous chemicals such as heavy metals and microplastics, requiring effective solutions to restore the quality of aquatic ecosystems. Several mechanisms that occur during the phytoremediation process in reducing contaminants in water include phytoextraction, phytostabilization, phytovolatilization and rhizofiltration. The success of the phytoremediation process is influenced by plant characteristics, environmental conditions, and the nature of pollutants. The level of phytoremediation efficiency in reducing pollutants can be estimated using the percentage reduction formula. Observations on plant growth such as biomass weight, root length, and plant height are needed to evaluate plant health and symptoms of phytotoxicity that may arise due to contact with contaminants on plants. Laboratory analysis of spectroscopy or chromatography is needed to determine quantitative data on the accumulation of heavy metals or other hazardous substances.

Keywords: Pollution, Plant, Phytoremediation.

INTRODUCTION

Water pollution is a serious problem faced by Indonesia, where many water sources are contaminated by domestic, industrial and agricultural waste. According to the Asian Development Bank (2008), Indonesia experiences a loss of Rp 45 trillion per year including accumulated costs for health services, provision of clean water, and a decline in tourism image caused by water pollution (Chen et al., 2020). In 2022, it was reported that most rivers in Indonesia were polluted. Of the 111 rivers identified, only 9 rivers (8.1%) had water quality that met water quality standards(Yusuf and NUWSP, 2023). This occurs due to waste being dumped into water bodies without adequate treatment, causing water quality to decline drastically and resulting in negative impacts on human health and the ecosystem.

These sources of pollution include fecal waste, household waste, and hazardous chemicals such as heavy metals and microplastics (Selvam et al., 2021). Water pollution not only threatens public health by increasing the risk of infectious diseases such as diarrhea and cholera, but also damages biodiversity in waters (Lara et al., 2012). In addition, poor sanitation conditions and substandard waste disposal practices worsen the situation, especially in rural and peri-urban areas (Purnama et al., 2024). This is a serious challenge that requires effective solutions to restore the quality of aquatic ecosystems from pollution.

Phytoremediation is an innovative method that utilizes plants to address environmental pollution, particularly in the context of water pollution (Jain et al., 2019). With the increasing problem of pollution due to industrial activities, agriculture, and domestic waste, phytoremediation offers an environmentally friendly and low-cost solution. This process involves the use of plants that have the natural ability to absorb, accumulate, and decontaminate pollutants from polluted media such as soil and water. Plants act as cleaning agents through various mechanisms, including phytodegradation, phytostabilization, and rhizofiltration (Tonelli et al., 2022). Through this mechanism, pollutants such as heavy metals and organic compounds can be converted into less harmful forms or even completely removed from the environment. In addition, phytoremediation not only helps in cleaning pollutants but also improves soil and water quality, thus supporting the sustainability of the ecosystem (Bhat et al., 2022).

This article is designed to review and summarize the potential of phytoremediation as a sustainable and effective solution to overcome water pollution. Through a comprehensive literature review, covering the mechanism of phytoremediation, the effectiveness of various types of plants in absorbing pollutants, as well as challenges and opportunities in large-scale implementation. It is hoped that this article can provide in-depth insights for researchers, environmental practitioners, and policy makers regarding the importance of phytoremediation as an environmentally friendly and economical alternative to restore polluted aquatic ecosystems. en shown to increase the risk of serious diseases, including lung cancer, heart disease, and chronic respiratory disorders. In addition to health impacts, air pollution also contributes to climate change and environmental degradation, further worsening living conditions on our planet.

This study aims to analyze the impact of air pollution on public health, especially those caused by pollutants produced by motor vehicles. By understanding the relationship between air pollution and various health problems, it is hoped that the public can be more aware of the urgency of air pollution problems that occur around them. This awareness is important to encourage collective action in reducing vehicle emissions and improving air quality, so as to protect the health of individuals and the community as a whole. Through this study, it is hoped that the information obtained can be the basis for more effective public policies and environmental initiatives.

MATERIALS AND METHODS

This article is compiled using a review method to present a comprehensive analysis of phytoremediation in reducing water pollutants, examining the effectiveness of various types of plants in overcoming environmental contamination. In this article, the author collects and evaluates existing literature on the working mechanisms of plants in absorbing heavy metals and hazardous organic compounds, as well as the role of microorganisms in the rhizosphere that support the phytoremediation process.

RESULTS AND DISCUSSION

Phytoremediation

Phytoremediation is a waste treatment technique that utilizes the ability of plants to absorb, accumulate, and remove pollutants from the environment, both soil and water (Hooda, 2007). This method focuses on the use of various types of plants that have special abilities to tolerate and overcome contaminants, such as heavy metals, pesticides, and hazardous organic compounds. These plants play an active role in the bioremediation process by utilizing their natural mechanisms to improve environmental quality (Marzuki et al., 2022).

Phytoremediation mechanisms in reducing contaminants in wastewater consist of phytoextraction, phytostabilization, phytovolatilization and rhizofiltration. Phytoextraction is the absorption and removal of contaminants by plant roots from the environment and translocation into harvestable plant biomass (Tonelli et al., 2022). Phytostabilization is the reduction of the mobility and bioavailability of pollutants in the environment by both physical and chemical effects such as soil pH control, precipitation, absorption, humification and lignification of organic compounds. Phytovolatilization is the process of pollutant absorption by plants and evaporation into the atmosphere by the leaf system. Rhizofiltration is the use of plant roots to absorb or adsorb contaminants present in solutions around the root zone.

1. Phytoextraction

   Phytoextraction is a phytoremediation process in which plants absorb contaminants from contaminated soil or media and translocate them to the upper parts of the plant, such as leaves and stems. This mechanism involves several steps, starting with the uptake of contaminants through the roots, where harmful substances such as heavy metals accumulate. Once the contaminants are absorbed, the plant will transport them through the vascular system to the upper parts, allowing for higher accumulation in the leaves and stems (Weis and Weis, 2004). This process not only helps clean contaminated soil but also allows for more sustainable and environmentally friendly waste management. A concrete example of phytoextraction can be seen in the use of hyperaccumulator plants, such as *Alyssum murale* and *Thlaspi caerulescens*, which are known to absorb large amounts of heavy metals such as nickel and zinc. Studies have shown that Alyssum murale can accumulate up to 10,000 mg/kg of nickel (Konakci et al., 2023). making it an ideal choice for remediation of nickel-contaminated soil. Once the accumulation process is complete, the plants can be harvested and burned to remove the retained contaminants, or used in other processes to recover the accumulated metals.

2. Phytostabilization

   Phytostabilization is one of the mechanisms in phytoremediation that aims to stabilize contaminants in the soil without absorbing them into the plant body. This process involves plants converting pollutants into non-toxic compounds, thereby preventing the movement of contaminants into groundwater or air (Latif et al., 2023). Plants used in phytostabilization can bind contaminants to their roots, thereby reducing mobility and the potential for further contamination (Neneng and Saraswati, 2019). This mechanism is very effective for decontamination of inorganic substances such as heavy metals, and are often applied in areas contaminated by industrial or mining activities(Alvarenga et al., 2009). A concrete example of the application of phytostabilization can be seen in the use of plants such as sunflowers (*Helianthus annuus*) (Chen et al., 2020) and various types of grass to overcome heavy metal pollution at reclamation sites (Purwantari, 2007). These plants are able to stabilize heavy metals by depositing contaminants in their root zone, preventing them from being carried away by water flow. In addition, this process also helps improve soil structure and increase fertility, making it more ready for replanting. Thus, phytostabilization not only serves as an environmental cleanup method but also supports the rehabilitation of degraded land due to pollution (Marzuki et al., 2022). At this stage, there are microorganisms that play an important role in helping plants absorb and process pollutants from polluted environments. They contribute through several mechanisms, including biosorption and bioaugmentation. Microorganisms associated with plant roots, such as bacteria and fungi, can increase the ability of plants to degrade or accumulate contaminants, such as heavy metals and hazardous organic compounds (Fester et al., 2014). In the phytoremediation process, plants will release root exudates that create an environment that supports the growth of microbes in the rhizosphere. These exudates provide a food source for microorganisms, which in turn can help in the degradation of pollutants. In addition, the rhizodegradation process occurs when microorganisms in the rhizosphere degrade pollutants into less harmful compounds, thereby increasing the overall effectiveness of the phytoremediation process (Wenzel, 2009).

3. Phytovolatilization

   Phytovolatilization is a phytoremediation mechanism in which plants are used to absorb contaminants from soil, water, or sediment, then convert them into a volatile form and release them into the atmosphere. This process involves the uptake of contaminants by plant roots, followed by transport through plant tissues until they reach the leaves, where the contaminants or their degradation products are released into the air along with water vapor through the process of transpiration (Meena et al., 2021). This mechanism is often used to handle contaminants such as mercury, selenium, and other volatile organic compounds. Phytovolatilization works effectively on pollutants that can be converted into gaseous form by plant metabolism. A concrete example of phytovolatilization is the use of plants such as *Brassica juncea* (Raj et al., 2020) and Populus deltoides (Beals, 2021) to address mercury contamination in the soil. This plant is able to absorb inorganic mercury from the soil and convert it into the volatile form of methylmercury, which is then released into the atmosphere. In addition, poplar trees have also been used to remove volatile organic compounds such as trichloroethylene (TCE) from contaminated groundwater.

4. Rhizofiltration

   Rhizofiltration is a phytoremediation process that uses plant roots to absorb, adsorb, or precipitate contaminants from water or soil solutions. In this mechanism, plant roots act as filters that trap contaminants, forming a thin layer on the surface of the roots. This process is effective in removing heavy metals and toxic substances from polluted water. Rhizofiltration is very similar to phytoextraction, but the difference lies in the polluted media; rhizofiltration is used in water bodies, while phytoextraction is used in soil (Sharma and Pandey, 2014). Rhizofiltration applications can be done by planting phytoremediation plants directly on the surface of polluted water or by flowing polluted water into a greenhouse media where phytoremediation plants grow optimally. A concrete example of rhizofiltration is the use of aquatic plants such as water hyacinth (*Eichhornia crassipes*) (Banerjee and Roychoudhury, 2022) or water lettuce (*Nasturtium officinale*) (Abollino et al., 2024) to clean liquid waste. The roots of this plant absorb and accumulate heavy metals such as copper (Cu)1, cadmium (Cd), and lead (Pb) from water, thereby reducing the concentration of pollutants. The mangrove plant Rhizophora mucronata also shows a rhizofiltration mechanism in accumulating copper metal in its roots1. Once the plant roots are considered to have sufficiently accommodated pollutants, the plant can be harvested and burned.

The average time required for the phytoremediation process varies depending on the type of plant used, the type of contaminant, and environmental conditions. However, in general, phytoremediation lasts for an average of 2 to 14 days (Nedelkoska and Doran, 2000). For example, the use of plants such as *Echinodorus palaefolius* in one study showed that the effectiveness of reducing iron levels in well water was achieved within 14 days (Evangelista and Hasan, 2021). On the other hand, another study showed that a batch culture system with hydromacrophytes can improve water quality within six days (Retnaningdyah and Arisoesilaningsih, 2019). Therefore, the duration of the phytoremediation process is highly dependent on various factors and can be adjusted to the specific needs of the remediation project being undertaken.

Factors Affecting Effective Phytoremediation

The success of phytoremediation is influenced by various interacting factors, ranging from plant characteristics, environmental conditions, to the nature of the pollutants themselves. The ability of plants to accumulate various types of pollutants with different concentrations is a key factor. In addition, the chemical and physical properties of the soil, as well as the physiological properties of the plants also play an important role. The amount of hazardous chemicals in the environment also determines the effectiveness of phytoremediation, as well as the mechanisms of accumulation and hyperaccumulation which are reviewed physiologically, biochemically, and molecularly (Siciliano and Germida, 1998). The use of the right waste concentration is also crucial for the success of this process. Not all plants can be used because each plant has different metabolic, volatilization, and pollutant accumulation capabilities.

Environmental conditions also play an important role in determining the efficiency of phytoremediation. Factors such as temperature, pH, electrical conductivity, organic matter, and number of plants affect the effectiveness of the phytoremediation process (Maulana, 2023). Environmental temperature, for example, can affect plant transpiration during phytoremediation, which in turn affects pollutant transport and bioconcentration. Plant transpiration rates are the most important means of purifying pollutants in phytoremediation. In addition, a large number of plants in a water body can absorb pollutants better than a small number of plants.

In addition to the above factors, the interaction between plants and microorganisms in the rhizosphere is also important for the success of phytoremediation. Microorganisms associated with plant roots can help in degrading pollutants (Fouad et al., 2022). The bioavailability of metals in the rhizosphere and the rate of metal uptake by roots are also limiting factors in metal phytoextraction (Kidd et al., 2009). The selection of the right plants is also based on properties such as fast growth, the ability to consume large amounts of water in a short time, the ability to remediate more than one pollutant, and high tolerance to pollutants (Sarwar et al., 2017; Jeevanantham et al., 2019; Kafle et al., 2022).

Efficiency of phytoremediation application

To determine the level of phytoremediation efficiency in plants, several methods can be used, including analysis of pollutant concentration reduction, plant growth measurement, and plant health evaluation. One common method is to calculate the effectiveness of pollutant absorption using a formula that compares the initial concentration and the final concentration of the pollutant after a certain period. For example, in a study using water hyacinth (*Eichhornia crassipes*), effectiveness can be calculated using the formula:

$$E = \frac{C_0 - C_n}{C_0} \times 100\% \tag{1}$$

where Co is the initial concentration of pollutants and Cn is the concentration of pollutants on the last day of observation. In this way, the efficiency of phytoremediation can be expressed in percentage which gives a clear picture of how effective the plants are in reducing contaminants.

Plant growth measurements such as biomass weight, root length, and plant height are also important to evaluate plant health and development during the phytoremediation process (Salam et al., 2016). Good growth indicates that plants are not only able to absorb pollutants but also remain healthy despite being exposed to hazardous substances (Chaudhry et al., 2005). Morphological observations such as changes in leaf color or phytotoxicity symptoms can also provide additional information regarding the impact of contaminants on plants.

Laboratory analysis of pollutant content in plant tissue after phytoremediation can provide quantitative data on the accumulation of heavy metals or other hazardous substances. Analytical methods such as spectroscopy or chromatography can be used to measure metal concentrations in plant roots, stems, and leaves. By combining all these data, researchers can comprehensively assess the efficiency of phytoremediation carried out by certain plants in overcoming environmental pollution.

Common Plants Used in Phytoremediation

Phytoremediation is an innovative and environmentally friendly method to address soil and water pollution by utilizing plants' ability to absorb, accumulate and transform pollutants. Some commonly used plants in this process include *Zinnia elegans, Jatropha curcass, and Ipomoea aquatica* each of which has advantages in addressing different types of contaminants such as heavy metals and organic waste. These plants not only contribute to environmental restoration, but can also improve the quality of surrounding soil and water.

Zinnia elegans and Impatiens balsamina are two ornamental plants that show significant potential in the phytoremediation process, especially to overcome heavy metal pollution such as mercury and cadmium. *Zinnia elegans* was able to reduce mercury levels in soil from 0.2621 µg/g to 0.188 µg/g, with mercury accumulation in plants reaching 0.0641 µg/g (Innah, Umar, et al., 2023). Meanwhile, Impatiens balsamina successfully reduced soil mercury levels to 0.1223 µg/g and absorbed 0.1641 µg/g of mercury in plant tissues1. In addition, another study also found that Impatiens balsamina can accumulate cadmium with an absorption efficiency of 24.64%, demonstrating its ability to clean polluted soil (Juhriah et al., 2023). These two plants not only contribute to environmental restoration but can also grow well in contaminated soil conditions, making them attractive options for phytoremediation applications.

Hanjuang plants (*Cordyline fruticosa*) have been proven effective in the phytoremediation process, especially to reduce heavy metal contamination such as lead (Pb) and cadmium (Cd). Research by Juhriah et al., 2023 showed that Hanjuang can accumulate lead with bioaccumulation factor (BAF) values ranging from 0.33–1.01, as well as translocation factor (TF) of more than 1, indicating its ability to phytoextract the metal from soil. In addition, another study also found that Hanjuang was able to absorb cadmium with the highest accumulation in the roots reaching 36.2167 mg/kg at a concentration of 150 mg/kg after 42 days of treatment (Sari et al., 2019). The phytoremediation mechanism that occurs is a combination of phytoextraction and phytostabilization, making Hanjuang a promising option for heavy metal contaminated soil rehabilitation (Herlina et al., 2020).

The caladium plant (*Colocasia esculenta*) has been proven effective in phytoremediation, especially in addressing mercury pollution in the environment due to mining activities. *Colocasia esculenta* can accumulate mercury well, with a decrease in mercury concentration in sediment from 609.22 ppm to 12.40 ppm after phytoremediation treatment . In addition, mercury levels in the effluent also decreased from 596.11 ppm to 2.42 ppm, indicating the ability of this plant to clean up polluted environments. The results of the analysis using the T-Test test showed that there was a significant difference between mercury concentrations in plant roots before and after phytoremediation, indicating the effectiveness of *Colocasia esculenta* as a phytoremediation agent that can be used for the rehabilitation of contaminated land in river ecosystems (Mahmud et al., 2013).

Jatropha curcass proved effective in phytoremediation of heavy metals (Hg, Pb, Cd, Fe) through phytostabilization and phytoaccumulation mechanisms. Its effectiveness is supported by the ability of roots to absorb metals and optimal TF/BAF values. Research suggests its use for rehabilitation of polluted land, especially in mining areas (Surahmaida and Mangkoedihardjo, 2017). For example, *Jatropha curcass* effectively reduces mercury levels in traditional mining soils. The significant decrease in Hg in soil after 7–21 days of treatment, with statistical analysis (One Way Anova and LSD tests) showing a significance of 0.000. The dominant mechanism was phytostabilization, where Hg accumulated in the roots with Translocation Factor (TF) values <1 (Erusani et al., 2024). Another study recorded Hg accumulation in the roots reaching 7.83 mg/kg. Reduction of Pb levels in soil polluted by coal waste. Research by Nia Febrianti (2023) showed a decrease in Pb from 25.89 mg/kg to 14.40 mg/kg after acclimatization, with quantitative analysis using AAS. This plant also showed the potential for Pb phytoextraction with a Bioaccumulation Factor (BAF) value >1. Surahmaida's study (2017) proved that Jatropha reduces soil Cd levels by 76–91% and accumulates Cd in plant tissues up to 125%. Parameters measured include Cd concentration in soil, plant height, and leaf area.

This efficiency is supported by phytostabilization and phytoaccumulation mechanisms. Furthermore, research by Lelis Handayani (2022) found the highest Fe accumulation in roots (0.0598 mg/g) and leaves (0.0770 mg/g) after 7 days. TF values <1 indicate the dominance of phytostabilization, where Fe is immobilized in the roots to prevent dispersal to the environment.

Aquatic plants such as *Ipomoea aquatica* and *Eichhornia crassipes* generally have benefits in reducing pollutants in water. Water spinach: Optimal for absorbing heavy metals (Fe, Cd) and reducing TSS. The dominant mechanism involves accumulation in the roots (high BCF). Fe levels decreased from 1.40 mg/L to 0.61 mg/L (20 stalk variation) after 7 days of utilization. The highest Fe accumulation in the roots reached 937.5 mg/kg (Saleh, Zam, et al., 2024). This result was obtained after measuring Fe concentration using UV-Vis Spectrophotometry), bioconcentration factor (BCF), and translocation. Water Hyacinth effectively reduced organic parameters (BOD, COD, phosphate) with >90% efficiency in a short time (5–6 days). Phosphate concentration dropped to <0.01 mg/L in 5 days. Phosphate accumulation in roots (14.90%) and petioles (20.05%) (Stefhany, Sutisna, Pharmawati, 2013). Another study stated that there was a decrease in BOD (98.70%) and COD (98.60%) in 6 days (Ahmad and Adiningsih, 2019).

CONCLUSIONS

Phytoremediation is a green technology that uses plants to clean contaminated environments, such as soil and water, from harmful pollutants, including heavy metals and organic compounds. This process takes an average of 2 to 14 days, depending on the type of plant, the type of pollutant, and environmental conditions. Phytoremediation mechanisms include phytostabilization, where plants stabilize pollutants in the soil; phytodegradation, which involves breaking down pollutants into less harmful forms; and phytovolatilization, where pollutants are converted into gas and released into the atmosphere. The efficiency of phytoremediation is influenced by several factors, including the characteristics of the plants used, environmental conditions such as temperature and pH, and the nature of the pollutant itself, such as concentration and bioavailability. The level of efficiency of phytoremediation in reducing pollutants can be estimated using the percentage reduction formula. Observations on plant growth such as biomass weight, root length, and plant height are needed to evaluate plant health and possible phytotoxicity symptoms due to contact of contaminants on plants. Spectroscopic or chromatographic laboratory analysis is required to obtain quantitative data regarding the accumulation of heavy metals or other hazardous substances.

Author contributions

Nour Salah Abdeljawad, Rajeev Pratap Singh: Conceptualization, analysis, draft writing, and editing.

Conflict of Interest

There is no conflict of interest in this study.

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Data availability

Data related to the findings of this study are available at the corresponding author.

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