MALAYSIAN JOURNAL OF APPLIED SCIENCES 2023, VOL 8 (2): 111-135
E-ISSN:0127-9246 (ONLINE)
http://dx.doi.org/10.37231/myjas.2023.8.2.373
https://journal.unisza.edu.my/myjas

REVIEW ARTICLE

Viability and Efficacy of Phytoremediation for Ecological Rehabilitation: A review

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Received: 20/8/2023, Accepted: 06/09/2023, Available Online: 31/10/20223

Abstract

The debate regarding the effectiveness, cost-efficiency, and applicability of phytoremediation, a plant-based environmental treatment, is gaining momentum. Phytoremediation involves the use of plants, microbes, nutrients, and agronomic techniques to manage and neutralize contaminants in soil, sediment, and water resources. Its objectives encompass soil stabilization, erosion control, and the improvement of wildlife habitats. Plants possess the capability to absorb, translocate, modify, and immobilize hazardous metals, reducing their toxicity and environmental impact. This method is increasingly adopted in industry today due to its cost-effectiveness and ecological friendliness. Nevertheless, it is undeniable that every process has its own set of advantages and disadvantages, and there is no flawless approach. Therefore, this review aims to provide environmental science researchers with a comprehensive understanding of the strengths and weaknesses of phytoremediation.

Keywords: Phytoremediation, hazardous waste, environmental treatment, cost-efficiency, ecological rehabilitation

Introduction

Phytoremediation, as an environmental technology, harnesses the natural power of plants to eliminate, break down, or immobilize pollutants in soil and groundwater (Berti & Cunningham, 2000). In an era of escalating environmental concerns and the imperative for sustainable remediation solutions, this approach has gained significant traction as an alternative to traditional remediation methods (Kafle et al., 2022). The plant species employed in phytoremediation exhibit the remarkable ability to absorb, degrade, or immobilize a diverse array of contaminants, including heavy metals, herbicides, pesticides, and hydrocarbons, all the while enhancing the overall quality of soil and water resources (Solomou et al., 2022). It's crucial to note that phytoremediation is a safe and non-invasive remediation method, capable of restoring ecosystems in contaminated sites (Ashraf et al., 2019).

The concept of phytoremediation was introduced by Dr. Ilya Raskin of Rutgers University in 1991 when he proposed this innovative approach in a grant proposal for the US Environmental Protection Agency's (EPA) Superfund Program. Subsequent research, supported by Raskin et al. (1994), explored the potential of plants to remediate soil and water contaminated with heavy metals, recognizing their unique capacity to purify the environment by removing pollutants. Early investigations delved into understanding how various metals and radionuclides affected the ability of plants to absorb contaminants while maintaining their viability (Singh et al., 2022). As the field advanced, researchers expanded their focus to assess different plant species and varieties, with the goal of identifying the most suitable plants for phytoremediation.

In the early 1990s, this pioneering research led to the development of various phytoremediation technologies, including phytoextraction, rhizofiltration, phytovolatilization, and phytostabilization. These techniques have since become integral components of the phytoremediation toolbox. Today, phytoremediation stands as a well-established and increasingly utilized technology for remediating contaminated sites (Meers et al., 2008; Nissim & Labrecque, 2021; Bhat et al., 2022).

Phytoextraction, one of the key phytoremediation methods, capitalizes on plants' capacity to absorb contaminants from both soil and water. This process involves the uptake of pollutants by plant roots, followed by their transport to the aerial parts of the plant, where contaminants are stored in leaves, stems, and fruits (Suman et al., 2018). Rhizofiltration, on the other hand, deploys plants to extract pollutants from water sources by having their roots take up contaminants, which can then be released into the atmosphere or soil (Rao et al., 2022). Phytovolatilization represents another phytoremediation technique, wherein plants convert contaminants into non-toxic gases that are subsequently released into the atmosphere (Cristaldi et al., 2020). Lastly, phytostabilization employs plants to contain pollutants in the soil, preventing their migration into groundwater or their release into the atmosphere (Zgorelec et al., 2020). These various approaches collectively highlight the versatility and potential of phytoremediation in addressing a wide range of environmental contamination challenges.

Mechanism of Phytoremediation

Phytoremediation is a natural process that can be used to reduce air, soil, and water pollutants without harming the environment, making it a useful and sustainable technique for decontaminating polluted mediums (Kong & Glick, 2017; Babu et al., 2021; Silvestrin, 2022). As part of the process, pollutants are absorbed by the roots, accumulated in bodily tissues, degraded, and transformed into less harmful forms (Favas et al., 2018; UNEP, 2019; Vidal et al., 2019; Yadav et al., 2018). This approach is effective in remediating dirt, sludge, and sediment, and can remove a wide range of contaminants (Kong & Glick, 2017) and it is a significantly safer option (Najeeb et al., 2017).

This approach involves the use of natural plant processes to remove contaminants, which is eco-friendlier and less expensive than chemical or physical techniques. This technique also requires less equipment and personnel than conventional approaches since plants perform the majority of the job (Ali et al., 2020). Therefore, it is a viable option for sites that are difficult or expensive to treat using other methods (Dadrasnia et al., 2013).

Furthermore, the advantage of this approach is the avoidance of soil excavation and groundwater pumping, thus conserving energy and resources (Zodrow, 1999). The implementation of phytoremediation using various plant species, including smaller ones, contributes to addressing issues like soil erosion control, site beautification, noise reduction, and enhancement of air quality in the vicinity (Farraji et al., 2020).

Various techniques are available for phytoremediation, each with its unique mechanism for eliminating contaminants (Pandey & Bajpai, 2019). For instance, certain methods involve the utilization of plants with a heightened ability to uptake and accumulate contaminants, such as heavy metals or radioactive isotopes, within their tissue. Following the absorption of contaminants by these plants, they can be harvested and disposed of safely, effectively eradicating the pollutants from the environment.

Besides, phytodegradation and phytovolatilization are part of the techniques that can be used to eliminate the contaminants. Phytodegradation technique employs plants able to degrade contaminants in their tissues, such as pesticides or chemical compounds. The plants digest the contaminants and transform them into harmless compounds (Stando et al., 2022). This approach uses plants to encapsulate contaminants in the soil, preventing their leaking into groundwater or evaporation into the atmosphere (Laghlimi et al., 2015). Phytovolatilization is a technique converts pollutants into gases that can be safely discharged into the atmosphere by using plants (Zhang et al., 2020).

Plants can remove pollutants from the soil or water in several ways, depending on the type of contaminant and the plant species (Gavrilescu, 2021). Here are some of the ways that plants can remove pollutants:

a) Absorption: Plants can absorb contaminants through their roots and store them in their tissues. This is known as phytoaccumulation (Abdel-Shafy & Mansour, 2018). The contaminants can then be removed by harvesting and disposing of the plant material.
b) Adsorption: Some contaminants can attach to the surface of plant roots, stems, or leaves through adsorption (Tripathi et al., 2020). The contaminants can then be removed by harvesting and disposing of the plant material.
c) Volatilization: Some contaminants can be taken up by the plant and released into the air through a process known as volatilization (Morra et al., 2011).
d) Rhizosphere biodegradation: Plants can stimulate the growth of microorganisms in the soil around their roots, which can break down contaminants through a process known as rhizosphere biodegradation.
e) Phytodegradation: Some plants can directly break down contaminants in their tissues through a process known as phytodegradation.

In general, plants break down contaminants through the action of enzymes produced by the plant or by microorganisms in the soil around the plant roots (Karigar & Rao, 2011). The contaminants are transformed into less harmful compounds, which can be taken up by the plant or released into the environment (Sharma, 2020).

Phytoremediation is often used in combination with other remediation methods, such as soil excavation or groundwater pumping, to achieve the most effective results (Sharma, 2018). The choice of plant species and the specific phytoremediation method used will depend on the type and concentration of the contaminant, the properties of the soil or water, and the specific conditions of the site.

Phytoremediation has been successfully used to remediate a variety of contaminated sites, including those contaminated with heavy metals, organic compounds, pesticides, and explosives (Rissato et al., 2015). Table 1 shows some examples of contaminated sites that have been successfully treated using phytoremediation.

Table 1. Examples of success story of phytoremediation

1) Phytoremediation in US	**Citation**
Issue: In 1997, there are almost half a million contaminated sites throughout the United States and more than 217,000 of them are still in need of remediation. Cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), and zinc are the most often encountered heavy metals at hazardous waste sites (Zn). Lead and mercury are two of the most dangerous pollutants, offering life-threatening risks to human health. Achievement: Phytoremediation has the potential to clean an estimated 30,000 contaminated waste sites throughout the US according to the EPA's Comprehensive Environmental Response Compensation Liability Information System (CERCLIS). Phytoremediation provides an innovative, economical, and environmentally friendly approach to removing toxic metals from hazardous waste sites.	Sharma & Pandey (2014); Raskin & Ensley (2000)
2) Phytoremediation in Indonesia	
Issue: Wastewater in coal mining company in South Kalimantan and generally in Indonesia. Achievement: Phytoremediation was reduced the acid levels in the water to raise the pH of acid mine average of 41% and lower levels of iron (Fe) with an average index bioremediation 7% and lower levels of manganese (Mn) with an average of 19% index bioremediation.	Herniwanti et al. (2013)
3) Phytoremediation in South Africa	
Issue: The concentrations of anthropogenic toxic substances in the environment has risen beyond set limits and difficult to ascertain, annual estimation of the spread has been reported to be in billions of tons. Achievement: Plants of phytoremediation are potential universal detoxifiers. It has been reported that plants in addition to accumulation of heavy metals, carry out intracellular degradation process which leads to decomposition of carbon skeleton of different contaminants.	Kvesitadze et al. (2004); Spaczynski et al. (2012)
4) Phytoremediation Australia	
Issue: The country faces environmental issues associated the disposal and treatment of sewage sludge and burgeoning landfills. Australia often suffers from drought and associated soil salinity, which can negatively affect plant growth. Achievement: Phytoremediation effective for the mitigation of leaching. Phytoremediation is best suited to the long-term clean-up of low value where other remediation options are prohibitively expensive.	Schnoor (2002)

Assessing the Advantages and Disadvantages of Phytoremediation Techniques

Phytoremediation can be a valuable tool for cleaning up contaminated environments, but it is important to carefully consider the pros and cons before deciding whether it is the best solution for a particular situation.

Advantages of Phytoremediation

i) Cost Effective and Sustainability

Phytoremediation is an effective, aesthetically pleasing, cost-effective, and ecologically friendly method for eliminating potentially dangerous metals from the environment. According to the United Nations Environment Program, phytoremediation is "the efficient use of plants to remove, decontaminate, or immobilise environmental contaminants" (UNEP, 2019). Phytoremediation is regarded as an effective, aesthetically pleasing, cost-effective, and ecologically sound process for the removal of potentially dangerous metals from the environment. In phytoremediation, plants absorb contaminants through their roots, which they subsequently move to their aboveground tissues (Ashraf et al., 2018). The great benefit of phytoremediation is that it is substantially less expensive than other conventional clean-up methods (Sabreena et al., 2022).

Phytoremediation procedures can remove numerous contaminants, including pesticides, chlorinated solvents, Polycyclic aromatic hydrocarbons (PAHs), Polychlorinated biphenyl (PCBs), petroleum hydrocarbons, radio nucleosides, surfactants, explosive components, and heavy metals (Hussain et al., 2018). It is also as a natural absorbent for pollutants and heavy metals (Pratas et al., 2014). Phytoremediation is the application of plants for the biological treatment of both organic and inorganic contaminants in non-urban and urban polluted soils. Phytoremediation is a significantly cheaper alternative to conventional clean-up methods, with very low operating expenses (expenses ranges from $0.02 to $1.00 per m^3 of soil (Gerhardt et al., 2017)), but still it appears to be underutilized (Montpetit & Lachapelle, 2015).

ii) Multiple uses

Phytoremediation serves numerous purposes including soil stabilisation, erosion management, and wildlife habitat improvement. Phytoremediation is the process of using plants to eliminate, degrade, or contain environmental pollutants (Yan et al., 2020). The plants can absorb, translocate, convert, and immobilise harmful metals, reducing their toxicity and environmental concentration (Singh et al., 2021). Phytoremediation is works well in removing heavy metals such as lead, cadmium, and zinc from the soil (Shehata et al., 2019). Degrading the organic pollutants for instance like pesticides and polychlorinated biphenyls (PCBs) (Aken et al., 2009).

Containing contaminants on-site, such as by employing plants to stabilize contaminated soils and prevent erosion, is the purpose of phytoremediation (Verma, 2021). Air pollutants, such as volatile organic compounds (VOCs) and carbon monoxide, can be eliminated or reduced using phytoremediation (Ravindra & Mor, 2022). Lakes and streams can become eutrophicated due to the presence of nitrogen and phosphorus, which can be removed from the water by phytoremediation (Kurniawan et al., 2022). Phytoremediation can be used as a source of biofuel (Tripathi et al., 2016). Phytostabilization is the use of plants to immobilize pollutants and limit their bioavailability in contaminated soils (Radziemska et al., 2020).

Table 2. Multiple uses of phytoremediation

Description	Citation
Plants possess the capability to uptake, transport, transform, and immobilize toxic metals, thereby diminishing their toxicity and environmental presence.	Singh et al. (2021)
Eliminate, degrade, or confine pollutants in the environment. Removing heavy metals like lead, cadmium, and zinc from the soil.	Yan et al. (2020) Shehata et al. (2019)
Stabilize contaminated soils and prevent erosion. Eliminate volatile organic compounds (VOCs) and carbon monoxide.	Olamilekan Lanre et al. (2020) Ravindra & Mor (2022)
Can be removed from the water by phytoremediation. Used as a source of biofuel.	Kurniawan et al. (2022) Tripathi et al. (2016)
To immobilize pollutants and limit their bioavailability in contaminated soils.	Radziemska et al. (2020)
Degrading the organic pollutants.	Aken et al. (2009)

Besides, phytoremediation can provide several environmental benefits, including its ability to reduce greenhouse gas emissions and its potential to preserve biodiversity (Hauptvogl et al., 2019). Here are some details on how phytoremediation can provide these benefits:

a) Reducing Greenhouse Gas Emissions: Phytoremediation can help to reduce greenhouse gas emissions in several ways (Zazai et al., 2018). First, phytoremediation avoids the need for energy-intensive and environmentally damaging traditional remediation techniques, such as excavation and disposal of contaminated soil, that produce greenhouse gas emissions (Grzegórska et al., 2020). Second, phytoremediation systems use plants to sequester carbon from the atmosphere, reducing the concentration of greenhouse gases in the atmosphere (Govindaraju et al., 2021). Finally, phytoremediation can restore degraded ecosystems, which can help to store carbon and reduce greenhouse gas emissions (Bai et al., 2022).

b) Preserving Biodiversity: Phytoremediation can also help to preserve biodiversity. Traditional remediation techniques, such as excavation and disposal of contaminated soil, can be highly disruptive to ecosystems and can result in the loss of habitat for many plant and animal species (Burger et al., 2020). In contrast, phytoremediation can restore degraded ecosystems, providing habitat for a wide range of species (Spieles, 2022). Additionally, phytoremediation systems often use native plant species that are well-suited to the local ecosystem, which can help to support biodiversity by preserving native plant species and the animals that rely on them.

iii) Non-invasive and non-destructible

Phytoremediation is the direct utilisation of living green plants; it is an efficient, inexpensive, non-invasive, and ecologically benign method for transferring or stabilising all hazardous metals and environmental pollutants in polluted soil or ground water (Mosa et al., 2016). Non - invasive phytoremediation refers to the use of plants that do not affect the ecosystem and do not require environmental modification to be effective (Ite & Ibok, 2019). Typically, non-invasive plants are native to the area and can survive without additional water, fertiliser, or other inputs (Mayfield et al., 2021). Some examples of non-invasive plants that can be used for phytoremediation include sunflowers, poplars and willows, ferns, sedges, marsh, and grasses (Herath & Vithanage, 2015).

Sunflower can remove heavy metals, such as lead, from soil (Dhiman et al., 2017). The Pb and Cd concentrations in sunflower shoots and roots rose as soil metal concentration increased from 0 to 200 mg kg^{1} soil. The greatest Cd (65.7 and 71.3 mg kg^{1} Dwt) and Pb (40.10 and 107 mg kg^{1} Dwt) levels were found in the shoot and root of plants growing in soil treated with

200 mg of metal (Alaboudi et al., 2018). Poplars and willows have the potential to be utilized for the in-situ decontamination of Cd-contaminated soils, such as pasturelands fertilized with Cd-rich superphosphate fertilizer (Pilipović et al., 2015). Clones of poplar (Kawa & Argyle) and willow (Tangoio) were cultivated in soils with a range of Cd contents (0.6–60.6 g g^1 dry soil). The willow clone accumulated much more Cd (9–167 g g^1 dry matter) than the two poplar clones (6–75 g g^1 dry matter), which did not vary from one another statistically. Poplar (Beaupré) trees collected in situ from a contaminated location were discovered to accumulate large amounts (up to 209 g g^1) of Cd (Robinson, 2000). Ferns can absorb and contain radioactive isotopes, such as cesium-137, in soil (Steinberg, 2010).

The potential of ferns to absorb and store radioactive isotopes, such as cesium-137, from contaminated soil has been researched (Butkus & Konstantinova, 2005). This is because fern fronds and roots have a high potential for uptake and storage of these isotopes. Through phytoremediation, ferns can absorb radioactive isotopes from soil. This involves the use of plants to purify polluted soil or water by absorbing or degrading contaminants. Due to their tremendous potential for absorbing and accumulating contaminants in their tissue, ferns are ideally suited for this process. Ferns are also capable of hyperaccumulating radioactive isotopes in their fronds and roots, meaning they can store radioactive isotopes at large quantities within their tissue without incurring any ill consequences. They can effectively remove radioactive isotopes from contaminated soil, which makes them suitable for phytoremediation. Sedges can take excess nutrients from water, such as nitrogen and phosphorus, so preventing eutrophication. In contaminated areas, the ability of above-ground tissues to remove N and P was greater (11.9 and 3.8 g/m^2, respectively) than in unpolluted areas (7.1 and 3.4 g/m^2, respectively). The high nutrient content of sedge plant's standing stock supports its potential use for nutrient removal in eutrophic wetlands. Sedge tissues exhibited the highest removal efficiency for Na, K, and N in the summer, and for Ca, P, and Mg in the winter (Galal et al., 2022). Phytoremediation with non-invasive plants is regarded as a sustainable and eco-friendly method for decontaminating contaminated environments.

The effectiveness of phytoremediation using non-invasive plants can vary depending on several factors, such as the type and concentration of the contaminant, the properties of the soil or water, the specific plant species used, and the conditions at the site (Nguyen et al., 2022). However, studies have shown that phytoremediation using non-invasive plants can be effective in reducing contaminant concentrations in soil and water (Khan et al., 2023).

iv) Adaptability

Adaptability of phytoremediation refers to the ability of the process to be modified or adjusted to suit different types of contaminants, soil conditions, and other factors. Table 2 shown a few factors effected adaptability plants of phytoremediation.

Table 3. Factors which are affecting the adaptability.

Description	Citation
Selection of plant species	Kafle et al. (2022)
Combination of multiple plant species	Smith et al. (2015)
Phytostabilization	Vives et al. (2005)
Phytovolatilization	Saleem et al. (2020)
Phytodegradation	Laghlimi et al. (2015)
Size and accessibility of the site	Vangronsveld et al. (2009)
Soil and water characteristics	Qayyum et al. (2020)
Climate	Saleem et al. (2020)
Type and concentration of contaminants	Laghlimi et al. (2015)

a) Selection of plant species: Different plant species have different abilities to remove different types of pollutants (Kafle et al., 2022). This indicates that the selection of plant species can be customised to the particular type of soil pollutant present (Kafle et al., 2022).
b) Combination of multiple plant species: A combination of multiple plant species can be used to remove different types of pollutants from the soil, which increases the adaptability of the process. Combination of multiple plant species are imperative so that can complement one another in the absorption of various toxins (Olowoyo, 2019). Create a diversified root system for soil improvement (Gao et al., 2016) and improve the overall stability and success of the phytoremediation process (DalCorso et al., 2019). Combination of multiple plant species are important because various plant species have varying capacity to absorb and digest certain pollutants (Pullagurala et al., 2018). By using a combination of species, a greater variety of pollutants can be remedied efficiently (Smith et al., 2015).
c) Phytostabilization: Phytostabilization is a method that uses plants to immobilize pollutants in the soil, preventing them from leaching into the groundwater (Bolan et al., 2011). This method is particularly useful for pollutants that are difficult to remove, such as heavy metals (Suman et al., 2018). Phytostabilization is essential to phytoremediation because it reduces the danger of human and animal exposure to toxins and reduces their environmental migration (Kowitwiwat & Sampanpanish, 2020). It involves the use of plants to encapsulate toxins in the soil and limit their spread, while also fostering the development of a healthy soil ecosystem (Rodríguez et al., 2022). This technology is more environmentally friendly and cost-effective than other cleanup techniques, and it can also give ecological and aesthetic benefits (Razzaq, 2017). It has been demonstrated that phytostabilization is effective at reducing the mobility of heavy metals in polluted soil and can also improve soil structure and fertility (Vives et al., 2005).
d) Phytovolatilization is a phytoremediation process in which plants absorb pollutants in the soil or water and subsequently release them as volatile molecules into the atmosphere (Wong, 2003; Marques et al., 2009). This method is deemed useful for eliminating toxins from the environment, notably volatile organic compounds (VOCs) (Limmer & Burken, 2016). Phytovolatilization is advantageous from an adaptation standpoint since certain plant species can tolerate and remove considerable amounts of toxins from the soil or water, offering it a cost-effective and environmentally benign alternative to conventional remediation techniques (Burken & Ma, 2006).
e) Phytodegradation: Phytodegradation is a process in which plants breakdown contaminants into less hazardous or non-toxic substances (Peuke & Rennenberg, 2005). This approach is useful for difficult-to-remove contaminants, such as certain types of pesticides (Kaur et al., 2021). In terms of adaptability, phytodegradation is advantageous since certain plant species can withstand and digest a wide variety of toxins, giving it a cost-effective and environmentally acceptable alternative to conventional remediation techniques (He et al., 2017). Additionally, it can improve the quality and fertility of the soil, making it an attractive alternative for long-term land management and restoration (Peng et al., 2018).
f) Combination of different phytoremediation methods: A combination of different phytoremediation methods can be used to remove pollutants from soil, air, and water (Salt et al., 1998). Multiple phytoremediation strategies can handle the specific problems provided by various pollutants and environmental conditions, resulting in more efficient and effective remediation outcomes (Liu et al., 2020). The combination of phytostabilization and phytodegradation improves the remediation of polluted soil in comparison to the use of individual phytoremediation techniques (Nedjimi, 2021). The study indicated that this strategy could decrease the concentration of pollutants in the soil and enhance soil quality and fertility (Zhou et al., 2019).

g) Site-specific considerations: Phytoremediation can be adapted to suit the specific conditions of a contaminated site, such as soil type, climate, and topography (Wei et al., 2021).
h) Soil and water characteristics: Soil type, pH, nutrient availability, and water availability can influence plant development and the ability to remediate a polluted site (Qayyum et al.,2020).
i) Climate: Temperature and precipitation patterns can affect the growth and survival of phytoremediation plants (Saleem et al., 2020).
j) Type and concentration of contaminants: Different contaminants may necessitate the use of distinct plants or treatment procedures for successful phytoremediation (Laghlimi et al., 2015).

Overall, phytoremediation is a flexible and adaptable strategy for cleaning up contaminated places because to its adaptability. Notably, the adaptability of the method is contingent on the availability of compatible plant species, and the method's unique suitability must be examined on a case-by-case basis.

Disadvantages of Phytoremediation

As mention in the previous sub-section, phytoremediation has many benefits, including cost-effectiveness and environmental friendliness, but there are also some disadvantages to its application. Generally, some of the limitations of this approach include:

i) Limited efficiency for certain pollutants

Phytoremediation is a slow process because it relies on the growth and metabolism of plants to remove or break down contaminants in the soil or water (Suresh & Ravishankar, 2004). The rate of remediation depends on the type and concentration of the contaminant, the type of plant, and the environmental conditions (Macci et al., 2020). This process can take a long time, depending on the type of pollutant, the concentration of the pollutant, and the type of plants being used (Cheng et al., 2015). Additionally, some plants may not be well-suited for certain types of pollutants, further slowing down the process (Wani et al., 2023). Other factors that can affect the speed of phytoremediation include the climate, soil conditions, and the availability of nutrients for the plants. Phytoremediation is considered a slow process for several reasons as shown in Table 4.

Table 4. Reasons slow process of phytoremediation

Description	Citation
Plants grow at a natural pace and cannot be rushed.	Wei et al. (2017)
Some pollutants may take longer to break down or remove than others	Beans (2017)
Some plants may not be well-suited for the type of pollutant present in the soil	Domene (2016)
Phytoremediation relies on the availability of nutrients in the soil	Shrestha et al. (2019)
Climate condition also play a role in the process of phytoremediation	Delgado-González et al. (2021)
Concentration of the pollutant also affects the speed of the process	Alwi & Manan (2013)

a) Plants grow at a natural pace and cannot be rushed (Beans, 2017). The time it takes for a plant to reach maturity and begin to break down or remove pollutants can vary (Wei et al., 2017).

b) Some pollutants may take longer to break down or remove than others (Beans,2017). For example, heavy metals such as lead and cadmium can be difficult to remove from the soil and may require multiple growing seasons (Tchounwou et al., 2012).
c) Some plants may not be well-suited for the type of pollutant present in the soil (Domene, 2016). This can slow down the process, as the wrong plant species may not be effective at removing or breaking down the pollutant (Supreeth, 2021).
d) Phytoremediation relies on the availability of nutrients in the soil (Shrestha et al., 2019). If the soil is too contaminated or lacks the necessary nutrients, the plants may not grow properly and the process will be slowed (Kozlov, 2004).
e) Climate condition also play a role in the process of phytoremediation, in cold and dry condition the growth of plant will be slow, this will slow down the phytoremediation process (Delgado-González et al., 2021).
f) The concentration of the pollutant also affects the speed of the process, high concentration takes longer to remediate (Lone et al., 2008).

The slow process of phytoremediation can have several impacts:

a) Financial impact: The longer it takes to clean up a contaminated site, the costlier the project will be. This can be a significant financial burden for organizations and governments responsible for the clean-up (Barrieu et al., 2017).
b) Environmental impact: If a contaminated site is not cleaned up quickly, the pollutants can continue to spread and cause harm to the environment and the health of local communities (Manisalidis et al., 2020).
c) Community impact: A contaminated site can be an eyesore and a source of concern for local residents. The slow process of phytoremediation can prolong the presence of the pollutants and the negative impact on the community (Bezirtzoglou et al., 2011).
d) Health impact: Contaminants can be harmful to human health, so the slower the clean-up process, the longer people are exposed to these harmful substances (Jaishankar et al., 2014).
e) Legal impact: Many countries have strict laws and regulations regarding the clean-up of contaminated sites, and failure to comply with these regulations can result in fines and legal action (Speight, 2017). Slow progress in phytoremediation may result in non-compliance with these regulations (Cunningham et al., 1997).

While phytoremediation can be an effective and sustainable method of remediation, it is important to carefully consider the type of pollutant, its concentration and soil or water conditions when selecting plant species for phytoremediation (Razmi et al., 2021). Not all plants are suitable for all types of contamination, and the effectiveness of phytoremediation can depend on the specific site conditions (Raklami et al., 2022). Certain plants are better at remediation than others. Some plants are unable to tolerate high levels of certain contaminants or are not effective at removing them (Koptsik, 2014). Phytoremediation is often location-specific and may not be feasible in all areas (Licinio et al., 2022). For example, in areas with high rainfall, contaminants may leach out of the soil or plants may not be able to grow.

ii) Lack of understanding of the underlying mechanism process

Phytoremediation has limited applicability in certain situations. Some of the main factors that can limit its use include:

a) Type of pollutant: Phytoremediation is most effective for removing certain types of pollutants, such as heavy metals and organic compounds (Mani and Kumar, 2014). It is less effective for removing other types of pollutants, such as radioactive materials or certain types of pesticides (Yadav & Kumar, 2019).

b) Concentration of pollutant: Phytoremediation may not be effective if the concentration of the pollutant is too high. High concentrations of pollutants can be toxic to plants and can inhibit their growth (Copaciu et al., 2016).

c) Climate and soil conditions: Phytoremediation is most effective in areas with favourable climate and soil conditions (Nedjimi & Daoud, 2009). In areas with extreme temperatures or poor soil quality, it may be difficult to find plants that can thrive and effectively remove pollutants.

d) Size of the contaminated area: Phytoremediation is most suitable for small to medium-sized contaminated areas. Large-scale contaminated areas may require more extensive and expensive clean-up methods (Kruger et al., 1997)

e) Availability of suitable plant species: Phytoremediation is effective only when the right plant species are available for the type of pollutant present (Liu et al., 2018) Some pollutants may not have specific plant species that can effectively remove them.

f) Time frame: Phytoremediation is a slow process, and it may not be suitable in situations where a quick clean-up is required, such as emergency spills or other urgent situations (Suresh & Ravishankar, 2004).

iii) Exposure associated with planting, maintenance, and monitoring

Maintenance of phytoremediation refers to the ongoing actions and efforts required to ensure the continued effectiveness of the phytoremediation process (Aransiola et al., 2019). Some of the main elements of maintenance include:

a) Watering and fertilizing: Plants need water and nutrients to survive and grow. Regular watering and fertilizing will ensure that the plants are healthy and able to effectively remove pollutants from the soil.

b) Pest and disease management: Pests and diseases can harm or kill plants, reducing their effectiveness in removing pollutants. Regular monitoring and management of pests and diseases is necessary to ensure that the plants are healthy.

c) Pruning and harvesting: Pruning and harvesting can help control the growth of the plants and prevent overcrowding. This can help ensure that the plants continue to thrive and effectively remove pollutants (Tosto et al., 2022).

d) Monitoring and testing: Regular monitoring and testing of the soil and water can help determine the effectiveness of the phytoremediation process. This can help identify any problems or areas that require additional attention (Jones, 2006).

e) Replanting: Over time, the plants used in phytoremediation may die or become less effective. Replanting with new, healthy plants is necessary to maintain the effectiveness of the process (Turner-Skoff & Cavender, 2019)

f) Maintenance of equipment: If any equipment such as irrigation system or drainage system is used during the phytoremediation process, it's also important to maintain and repair them as needed (Samer, 2015).

g) Cost: Maintaining a phytoremediation system can be costly, especially if it requires large amounts of water, fertilizer, or other inputs (Azubuike at el.,2016).

Overall, maintenance of phytoremediation is an ongoing process that requires careful planning and management to ensure that the plants are healthy and able to effectively remove pollutants from the soil. Phytoremediation systems are designed to use plants and soil microorganisms to remove or mitigate pollutants from the environment. Like any other environmental remediation system, phytoremediation systems require ongoing maintenance to operate effectively (Oh et al., 2014). The costs associated with phytoremediation system maintenance can vary depending on several factors, such as:

a) Size of the area treated: The larger the area being treated; the more maintenance will be required. This is because larger areas require more plants, more soil preparation, and more monitoring to ensure that the system is working effectively (Odoh et al., 2019).
b) Type of pollutant removed: The type of pollutant being removed will also affect the cost of maintenance. Some pollutants are more difficult to remove than others and may require more specialized equipment or monitoring to ensure that the phytoremediation system is operating effectively (Mendes et al., 2022).
c) Activity: The level of activity in the area surrounding the phytoremediation system can also impact the cost of maintenance. For example, if the area is highly trafficked, it may be necessary to regularly remove debris or trash that could interfere with the plants' ability to grow and remove pollutants.
d) Special maintenance required: Some phytoremediation systems may require specialized maintenance, such as regular soil testing or the use of specialized equipment to remove excess water or nutrients. These additional maintenance requirements can increase the cost of maintaining a phytoremediation system.

iv) Potential contamination of food product

There is potential for negative impact on the environment from the use of phytoremediation. Some of the potential negative impacts include:

a) Spread of invasive plant species: Some of the plants used in phytoremediation may be invasive, meaning that they can spread quickly and displace native plant species. This can have a negative impact on local biodiversity (Kumar & Singh, 2020).
b) Pesticide use: Pesticides may be used to control pests and diseases that affect the growth of plants used in phytoremediation. These pesticides can have negative effects on non-target organisms, including pollinators and other beneficial insects (Chin, 2010).
c) Nutrient leaching: Some plants used in phytoremediation can remove pollutants by taking them up into their tissues. However, this can also lead to the leaching of nutrients from the soil, which can have negative effects on other plant species in the area (Ali et al., 2013).
d) Changes in soil chemistry: Phytoremediation can also cause changes in the soil chemistry, which can affect the growth of other plant species and the ability of soil microorganisms to break down pollutants (Chibuike & Obiora, 2014).
e) Changes in soil hydrology: Phytoremediation can also cause changes in the soil hydrology, which can affect the groundwater and surface water in the area (Faubert et al., 2021).
f) Changes in soil structure: Phytoremediation can also cause changes in the soil structure, which can affect the growth of other plant species and the ability of soil microorganisms to break down pollutants (Bhat et al., 2022).

It's worth noting that, while there are potential negative impacts of phytoremediation, these impacts are generally considered to be relatively low when compared to other remediation methods. It's also important to conduct a thorough risk assessment before implementing any phytoremediation projects and to be mindful of the potential negative impacts throughout the process.

Contamination of food products can have negative health effects on consumers, and it is generally considered to be a serious issue (Rather et al., 2017). However, it is important to note that potential contamination of food products can also have a positive impact in some cases. Here are a few examples:

a) Early detection of contamination: Potential contamination of food products can lead to increased monitoring and testing of food products, which can help to detect contamination early and prevent contaminated products from reaching consumers.
b) Improved safety protocols: Contamination events can lead to increased scrutiny and improvements in safety protocols for food production and processing. This can help to prevent future contamination events and improve overall food safety.
c) Increased awareness: Contamination events can raise public awareness of food safety issues and the importance of safe food handling and preparation practices.
d) Innovation in food safety: The potential for contamination can also lead to increased innovation in food safety technology and processes, leading to better methods for detecting and preventing contamination.

Climate Dependent

Climate dependent of phytoremediation (Figure 1) refers to the fact that the success of the process is largely dependent on the climate conditions of the area where it is being used (O'Connor et al., 2019).

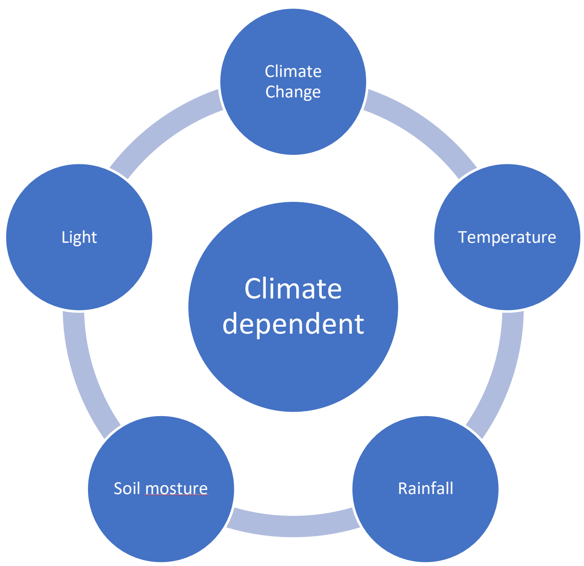

Figure 1. Climate dependent of phytoremediation

a) Temperature: Phytoremediation is most effective in areas with moderate temperatures (Liu & Tran, 2021). Extreme temperatures, whether hot or cold, can inhibit plant growth and reduce their ability to remove pollutants (Kennedy, 2004). Most phytoremediation plants grow best in moderate temperatures between 10 and 40 °C degrees (Pang et al., 2023). Higher temperatures can cause stress and reduce the plants' ability to absorb and metabolize pollutants (Ahmad et al., 2022). Conversely, extremely cold temperatures can cause the plants to go dormant, which can slow or halt the remediation process (Marković et al., 2021).
b) Rainfall: Adequate rainfall is necessary for the growth of plants used in phytoremediation. In areas with low rainfall, additional irrigation may be required (Al-Sayaydeh et al., 2022). Rainfall is important for phytoremediation because it provides water to the plants and can help to flush out pollutants from the soil. However, too much rain can lead to waterlogging, which can suffocate plant roots and inhibit their ability to remove pollutants (Elzenga & Van

Veen, 2010). Conversely, too little rainfall can cause the plants to wilt and die, which can also halt the remediation process (Oudin et al., 2005).

c) Soil moisture: The soil moisture level also plays an important role in the growth of plants and their ability to remove pollutants (Lee et al., 2017). The soil moisture level is also critical for phytoremediation because it affects the plants' ability to absorb and metabolize pollutants (Rostami & Azhdarpoor, 2019). The ideal soil moisture level for phytoremediation depends on the specific plant species being used and the soil type (Delgado et al., 2021).

d) Light: Most plants used in phytoremediation require adequate light to grow, and the process may not be effective in areas with low light levels (Luo et al., 2020).

e) Climate change: Climate change can also affect the effectiveness of phytoremediation by changing temperature, rainfall, and other conditions (James, 2022).

Climate dependent of phytoremediation can also impact the long-term maintenance of the process, as changes in climate conditions can affect the survival and growth of the plants used in the process. Additionally, the process may not be effective in certain areas where the climate is not suitable for the growth of the chosen plant species or for the type of pollutant present. It's worth noting that phytoremediation is not a one-size-fits-all solution and the specific suitability of the method needs to be evaluated on a case-by-case basis, considering the climate conditions of the area where it is being used.

Conclusion

In conclusion, phytoremediation is a promising and cost-effective way to clean up contaminated areas and reduce the number of hazardous materials released into the environment. However, there are potential drawbacks to using this process, such as the difficulty in controlling the growth of plants, the potential for invasive species to damage native ecosystems, and the possibility that certain contaminants may not be effectively removed. As such, it is important to carefully consider the potential benefits and drawbacks before implementing phytoremediation as a remediation strategy. Ultimately, phytoremediation may offer a viable solution for many contaminated areas, but further research and development is needed to ensure that it is used appropriately and with minimal adverse effects.

Acknowledgements

We express our gratitude to the Faculty of Bioresources and Food Industry for their invaluable support of this research endeavour.

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How to cite this paper:
Zakaria, M. Z., Azid, A., Samsudin, M. S., Ku Yusof, K. M. K. (2023). Viability and Efficacy of Phytoremediation for Ecological Rehabilitation: A review. *Malaysian Journal of Applied Sciences, 8(*2), 111-135.