



INNOVATIONS IN PHYTOREMEDIATION: APPLICATION OF ARTIFICIAL WETLANDS FOR THE CONTAMINATED WATER TREATMENT AND HEAVY METALS REMOVAL

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ABSTRACT

Objective: The objective of this study was a review to compile research on phytoremediation methods—including phytoextraction, rhizofiltration, phytostabilisation, phytodegradation, and phytovolatilisation—using primary sources to address heavy metal contamination in water.

Theoretical Framework: The study is a basic investigation that includes a contextualization regarding the water issue, as well as the treatment of wastewater. A description of the characteristics and quality indicators of water was carried out, along with the importance of the removal of contaminants such as heavy metals using different technologies like phytoextraction, rhizofiltration, phytostabilization, phytodegradation, and phytovolatilization. This led to a detailed description of artificial wetland techniques as a viable and sustainable alternative.

Method: The methodology adopted for this research includes data collection and compilation of existing information; regarding the different techniques related to wastewater treatment with artificial wetlands, these systems utilize natural processes involving vegetation, soil, and microbial activity to remove contaminants from water. More than 100 articles have been legally downloaded, and systematised in the database to paraphrase sentences and cite appropriately.

Results and Discussion: Phytoremediation is an environmentally friendly technical choice because of its low cost to remediate water and soil contamination through methods of phytoextraction, rhizofiltration, phytostabilisation, phytodegradation and phytovolatilisation for organic contaminants, pesticides, oil waste, heavy metals, antibiotics, etc. It is relevant to choose transgenic plant methods to insert DNA genes and conduct molecular mechanisms through experimental optimisation studies for lightened growth and hyperaccumulation of heavy metals, generating space for metal and biomass storage, and prior knowledge of the physiology and biochemical processes of the plants.

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Research Implications: The results can be applied or influence practices in environmental protection using Phytoremediation, which is based on a natural technique of plants and their microbiota associated with roots and tissues, endophytic bacteria as *Aeromonas* sp, *Pseudomonas* sp, *Bacillus* sp, *Sinorhizobium meliloti*, *Chryseomonas* sp, *Curtobacterium* sp, *Sphingomonas* sp, *Erwinia* sp, *Flavimonas* sp retain contaminants. On the other hand, aquatic macrophytes such as *Lemna* spp, *Typha* spp, *Potamogeton* spp, *Azolla filiculoides*, *Ceratophyllum demersum*, *Eichhornia crassipes*, and *Phragmites australis* constitute an effective and feasible complementary alternative for the treatment of contaminated waters.

Originality/Value: This study contributes to the literature. There are different phytoremediation methods such as phytoextraction, rhizofiltration, phytostabilisation, phytodegradation, and hytovolatilisation for organic contaminants, pesticides, petroleum waste, heavy metals, pharmaceutical antibiotics, etc. Each of the elements has specific applications depending on the conditions of the place and the type of contaminants in an ecosystem.

Keywords: Pollution, Water Quality, Heavy Metals, Phytoremediation, Artificial Wetlands.

INOVAÇÕES EM FITORREMEDIAÇÃO: APLICAÇÃO DE HUMEDAIS ARTIFICIAIS PARA O TRATAMENTO DE ÁGUAS CONTAMINADAS E REMOÇÃO DE METAIS PESADOS

RESUMO

Objetivo: O objetivo deste estudo foi revisar e compilar pesquisas sobre métodos de fitorremediação—incluindo fitoextração, rizofiltração, fitostabilização, fitodegradação e fitovolatilização—utilizando fontes primárias para abordar a contaminação por metais pesados na água.

Referencial Teórico: O estudo é uma investigação básica que inclui uma contextualização sobre a questão da água, assim como o tratamento de águas residuais. Foi realizada uma descrição das características e indicadores de qualidade da água, junto com a importância da remoção de contaminantes como metais pesados utilizando diferentes tecnologias como fitoextração, rizofiltração, fitostabilização, fitodegradação e fitovolatilização. Isso levou a uma descrição detalhada das técnicas de humedais artificiais como uma alternativa viável e sustentável.

Método: A metodologia adotada para esta pesquisa inclui a coleta de dados e a compilação de informações existentes; em relação às diferentes técnicas relacionadas ao tratamento de águas residuais com humedais artificiais, esses sistemas utilizam processos naturais que envolvem vegetação, solo e atividade microbiana para remover contaminantes da água. Mais de 100 artigos foram baixados legalmente e sistematizados na base de dados para parafrasear frases e citar adequadamente.

Resultados e Discussão: A fitorremediação é uma escolha técnica amiga do meio ambiente devido ao seu baixo custo para remediar a contaminação da água e do solo por meio de métodos de fitoextração, rizofiltração, fitostabilização, fitodegradação e fitovolatilização para contaminantes orgânicos, pesticidas, resíduos de petróleo, metais pesados, antibióticos, etc. É relevante escolher métodos com plantas transgênicas para inserir genes de DNA e conduzir mecanismos moleculares por meio de estudos experimentais de otimização para o crescimento acelerado e a hiperacumulação de metais pesados, gerando espaço para o armazenamento de metais e biomassa, e conhecimento prévio da fisiologia e processos bioquímicos das plantas.

Implicações da Pesquisa: Os resultados podem ser aplicados ou influenciar práticas de proteção ambiental utilizando a fitorremediação, que se baseia em uma técnica natural de plantas e sua microbiota associada às raízes e tecidos, como bactérias endofíticas como *Aeromonas* sp, *Pseudomonas* sp, *Bacillus* sp, *Sinorhizobium meliloti*, *Chryseomonas* sp, *Curtobacterium* sp, *Sphingomonas* sp, *Erwinia* sp e *Flavimonas* sp que retêm contaminantes. Por outro lado, macrófitas aquáticas como *Lemna* spp, *Typha* spp, *Potamogeton* spp, *Azolla filiculoides*, *Ceratophyllum demersum*, *Eichhornia crassipes* e *Phragmites australis* constituem uma alternativa complementar eficaz e viável para o tratamento de águas contaminadas.

Originalidade/Valor: Este estudo contribui para a literatura sobre os diferentes métodos de fitorremediação, como fitoextração, rizofiltração, fitostabilização, fitodegradação e fitovolatilização para contaminantes orgânicos, pesticidas, resíduos de petróleo, metais pesados, antibióticos farmacêuticos, etc. Cada um dos elementos tem aplicações específicas dependendo das condições do local e do tipo de contaminantes em um ecossistema.

Palavras-chave: Poluição, Qualidade da Água, Metais Pesados, Fitorremediação, Humedais Artificiais.



INNOVACIONES EN FITORREMEDIACIÓN: APLICACIÓN DE HUMEDALES ARTIFICIALES PARA EL TRATAMIENTO DE AGUAS CONTAMINADAS Y LA ELIMINACIÓN DE METALES PESADOS

RESUMEN

Objetivo: El objetivo de este estudio fue revisar y compilar investigaciones sobre métodos de fitoremediación-incluyendo fitoextracción, rizofiltración, fitostabilización, fitodegradación y fitovolatilización-utilizando fuentes primarias para abordar la contaminación por metales pesados en el agua.

Marco Teórico: El estudio es una investigación básica que incluye una contextualización sobre el problema del agua, así como el tratamiento de aguas residuales. Se realizó una descripción de las características e indicadores de calidad del agua, junto con la importancia de la eliminación de contaminantes como metales pesados utilizando diferentes tecnologías como fitoextracción, rizofiltración, fitostabilización, fitodegradación y fitovolatilización. Esto llevó a una descripción detallada de las técnicas de humedales artificiales como una alternativa viable y sostenible.

Método: La metodología adoptada para esta investigación incluye la recolección de datos y la compilación de información existente; respecto a las diferentes técnicas relacionadas con el tratamiento de aguas residuales con humedales artificiales, estos sistemas utilizan procesos naturales que involucran vegetación, suelo y actividad microbiana para eliminar contaminantes del agua. Se han descargado legalmente más de 100 artículos, y se han sistematizado en la base de datos para parafrasear oraciones y citar adecuadamente..

Resultados y Discusión: La fitoremediación es una opción técnica amigable con el medio ambiente debido a su bajo costo para remediar la contaminación del agua y el suelo a través de métodos de fitoextracción, rizofiltración, fitostabilización, fitodegradación y fitovolatilización para contaminantes orgánicos, pesticidas, desechos de petróleo, metales pesados, antibióticos, etc. Es relevante elegir métodos con plantas transgénicas para insertar genes de ADN y llevar a cabo mecanismos moleculares mediante estudios de optimización experimental para el crecimiento acelerado y la hiperacumulación de metales pesados, generando espacio para el almacenamiento de metales y biomasa, y el conocimiento previo de la fisiología y procesos bioquímicos de las plantas.

Implicaciones de la Investigación: Los resultados pueden aplicarse o influir en prácticas de protección ambiental utilizando la fitoremediación, que se basa en una técnica natural de plantas y su microbiota asociada a las raíces y tejidos, así como bacterias endofíticas como *Aeromonas* sp, *Pseudomonas* sp, *Bacillus* sp, *Sinorhizobium meliloti*, *Chryseomonas* sp, *Curtobacterium* sp, *Sphingomonas* sp, *Erwinia* sp, y *Flavimonas* sp que retienen contaminantes. Por otro lado, las macrófitas acuáticas como *Lemna* spp, *Typha* spp, *Potamogeton* spp, *Azolla filiculoides*, *Ceratophyllum demersum*, *Eichhornia crassipes*, y *Phragmites australis* constituyen una alternativa complementaria efectiva y viable para el tratamiento de aguas contaminadas.

Originalidad/Valor: Este estudio contribuye a la literatura sobre los diferentes métodos de fitoremediación, como la fitoextracción, la rizofiltración, la fitostabilización, la fitodegradación y la fitovolatilización para contaminantes orgánicos, pesticidas, desechos de petróleo, metales pesados, antibióticos farmacéuticos, etc. Cada uno de los elementos tiene aplicaciones específicas dependiendo de las condiciones del lugar y el tipo de contaminantes en un ecosistema.

Palabras clave: Contaminación, Calidad del Agua, Metales Pesados, Fitoremediación, Humedales Artificiales.

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1 INTRODUCTION

Water is an essential component for all forms of life including lakes, ponds, dams, canals, rivers, and streams. This resource is important because it provides three quarters of water for



agriculture and industries and one-third for households (Sasakova et al., 2018). However, water quality has deteriorated in recent years because of the discharge of industrial, agricultural, and domestic waste (Ayyam et al., 2019; G. Cheng et al., 2018); and other organic substances, such as nitrogen and phosphorus (Müller et al., 2020; Tang et al., 2022).

Furthermore, water scarcity and its contamination have become very frequent around the world (Babut et al., 2019), putting the availability of water resources at risk because of anthropogenic contamination (Renu et al., 2017). For instance, activities as industrial production or agricultural use of compounds containing heavy metals that increase environmental pollution (He et al., 2005; Zhou et al., 2019a, 2019) and affect life, especially human beings, through exposure (Armiento et al., 2020; Sacchi et al., 2020).

In developing countries, most industrial and domestic wastewater is discharged directly into waterways without treatment (Chen et al., 2022; Jiang et al., 2021). Consequently, these wastewater activities discharge have triggered the release of toxins, pharmaceuticals and personal protective equipment (PPE), endocrine disrupting chemicals (EDC), antibiotics, pathogenic microorganisms, and heavy metals into urban waterways (Babut et al., 2019b; Jiang et al., 2021).

Likewise, the impact of anthropogenic activities such as agriculture, mining and other industrial operations affects inland water ecosystems (Steffen et al., 2011). For this reason, 41% of marine ecosystems have been affected by heavy metal pollution (Halpern et al., 2008) that comes from industrial and environmental terrestrial mining sources, having social and economic repercussions (Ghadouani & Coggins, 2011).

Wastewater contaminated by heavy metals released into the atmosphere from various industries for example mining, stationery, electronics, pharmaceuticals, leather processing, hydrometallurgical, textile processing, batteries, electroplating, pesticides, and metal finishing with or without treatment (Qiao et al., 2020; Shan et al., 2020; Shao et al., 2020; Zhang et al., 2020). All of them alter the physical characteristics of water because of dissolved substances, generating an unpleasant odour with a dark appearance. They contain a high amount of total suspended solids (TSS) as well, affecting the irrigation water supply and causing the causes clogging and seasonal flooding

Currently, the demand for water increases worldwide every year due to population growth, deterioration of water resources and different types of contaminants in existing freshwater bodies (Lin et al., 2020; Xia et al., 2020). The availability of pure water is a fundamental need for human and animal life. In addition, it is essential to maintain aquatic life (Yang et al., 2017). Therefore, it is necessary to recover the water resources through the relevant



use of sustainable methods and techniques so that quality water can be ensured for human consumption in the long term to protect terrestrial and aquatic ecosystems and thus cover the water needs.

Phytoremediation is one techniques that allow plants to accumulate heavy metals to restore contaminated mainly sources as soils and waters (Bhat et al., 2022) because of the availability of trace elements that contribute significantly to the effectiveness of phytoremediation, which can be modulated by application of organic or inorganic fertilizers in soils and waters (Singh et al., 2022). Unlike physicochemical, biological techniques or constructed wetland (CW) technology have been used as an emerging, cost-effective and sustainable approach to widely treat municipal and industrial wastewater in recent years (Ashraf et al., 2017; Wang et al., 2020).

Constructed wetlands (CW) are ecological engineering wastewater treatment systems which are designed for natural water purification (Cheng et al., 2018), being an efficient and accessible remediation method (Hu et al., 2019; Liu et al., 2019), and they simulate natural processes, using aquatic macrophytes and microorganisms for water purification (Vymazal, 2009; Zhao et al., 2019; Zhuang et al., 2019).

Method: This research is a systematic review of journal articles from the Scopus, Web Of Science, and Scielo databases using the keywords: “water quality”, “polluted waters”, “heavy metals”, “phytoremediation”, “artificial wetlands” from primary sources as phytoextraction, rhizofiltration, phytostabilisation, phytodegradation and phytovolatilisation for the remediation of waters contaminated with heavy metals such as mercury, cadmium, chromium, arsenic, zinc, etc. Metals are widely dispersed in aquatic ecosystems because of the dilution of minerals from volcanic or sedimentary rocks and dilution of geothermal waters that are released into the environment, using descriptors: scientific writing and primary information sources containing scientific literature published through Digital Object Identifier (DOI).

2 THEORETICAL FRAMEWORK

2.1 DESCRIPTION OF WATER QUALITY CHARACTERISTICS

The physicochemical and bacteriological characteristics of water properties have an important role in water use for human consumption, irrigation, industrial use, and others (Parrone et al., 2020, Schwartz et al., 2019, Zhang et al., 2018,). These characteristics are a limiting factor



when developing certain anthropogenic activities in a country or region (Cheng et al., 2018). Referring to the surface water is scarcer and is distributed unevenly (Cheng et al., 2018). For this reason, physicochemical and bacteriological methods and analyses are used to evaluate water quality (Gabr et al., 2020, Varnier et al., 2017). On the other hand, temperature is a parameter used in the biodegradation of organic compounds in aquatic systems (Luo et al., 2022; Singh et al., 2022) and concerning the levels of dissolved oxygen (DO) in water (Souchon & Tissot, 2012) that can cause harmful alterations to ecosystems (Logan & Stillwell, 2018).

Although photosynthesis and respiration are the principal metabolic pathways that influence the hydrogen potential (pH) in aquatic habitats, it is necessary to highlight that it is an important ecological factor for the metabolic activities of water fauna that require a pH of 7.4 (Hamid et al., 2020). The pH is a component related to water turbidity that is an essential indicator of its quality and has important implications in the aquatic community in ecosystem turbidity levels (Zhang et al., 2021). On the other hand, Nitrogen (N) and Phosphorus (P) are the fundamental components for the development of plants and animals in terrestrial and aquatic ecosystems (Elser et al., 2007) since they cause eutrophication in wastewater that contain compounds such as solids in suspension (Turcios & Papenbrock, 2014).

Another relevant factor is the biochemical oxygen demand (BOD₅), in which the amount of dissolved oxygen (DO) decreases in the aquatic body, which is necessary for the stabilisation of organic waste in domestic and industrial environments (Nugraha et al., 2020). Likewise, microorganisms require an amount of oxygen to oxidise organic waste aerobically (Sonawane et al., 2020), which is correlated with the presence of thermotolerant coliforms in water. Among the indicators of faecal contaminants are *Escherichia coli*, enterococci, coliphages and clostridial sporoids, which reduce sulfite (Foppen & Schijven, 2006).

To monitor and evaluate water quality and contaminant levels (Meybeck, 2003), physicochemical and bacteriological parameters are used because of their practicality, effectiveness and accessibility (Uddin et al., 2021) through a national-level standardised normative value (Huang et al., 2021) such as the National Sanitation Foundation on quality guidelines of the Canadian Council of Ministry of Environment (Water Quality Indices, 2012).

2.2 IMPORTANCE OF HEAVY METALS AND THEIR TOXICITY

Water pollution increases the accumulation levels of heavy metals produced by various anthropogenic activities (Bortoloti & Baron, 2022; Sarwar et al., 2017a; J. Singh et al., 2021)



that generate harmful effects on environmental health. Therefore, heavy metals and metalloids are dangerous to human health, even at lower concentrations (Haferburg & Kothe, 2007), as mercury, chromium, cadmium, arsenic, lead, copper, zinc and nickel are toxic metals to living beings, and tend to accumulate in the food chain (Kara, 2005).

Heavy metals have gained importance worldwide because of their toxicity for living organisms, like bacteria that accumulate toxic Hg (monomethylmercury or dimethylmercury) that reduces water quality (Kumar et al., 2017) due to bioaccumulation (Bhat et al., 2022). However, plants depend on the concentration of heavy metals (Kanwar et al., 2023) since they require the absorption of micronutrients to survive.

These metals are composed of high atomic weight as mercury, chromium, cadmium, arsenic, lead, copper, zinc and nickel. Besides, the density is at least five times greater than water. They are naturally present in the layers of earth (Guzzi & La Porta, 2008). However, anthropogenic activities, such as industrial production or agricultural use of compounds that contain metals, increase this type of pollution (He et al., 2005; Zhou et al., 2019) and living beings due to exposure (Armiento et al., 2020; Sacchi et al., 2020).

Cd, Ni, Pb and other metals are widely found in wastewater (Eid et al., 2020) because of diffuse factors as emissions that have been recognized as the main reason for water pollution (Kelly et al., 1996). Recent studies demonstrated that untreated effluent water is a source of contaminated water with the presence of harmful elements such as Pb, Hg, Cr, As, and Cd that are toxic to human health and other living species if their concentrations exceed limits (Bansod et al., 2017).

Mercury (Hg) is one of the most abundant metals in the earth layer, occupying 66th place (Natasha et al., 2020) and is highly toxic to living beings. On the other hand, mining activities contribute enormously to Hg contamination of the soil and water of the entire ecosystem (De et al., 2014; Gray et al., 2004). The latest risk estimation studies predict possible entry routes into the food chain and health risks (Antoniadis et al., 2019; Tabassum et al., 2019).

On the other hand, arsenic (As) is a ubiquitous metalloid in the environment, used in various fields such as pesticides, electronic products, medicine, industry and metallurgy (Cheng et al., 2019; Garcia-Ordiales et al., 2018; Mandal & Suzuki, 2002; Matschullat, 2000). Likewise, lead (Pb) is one of the most recognized poisonous elements in soil and water, where plants absorb it and deposit it in the roots and leaves (Emamverdian et al., 2015).

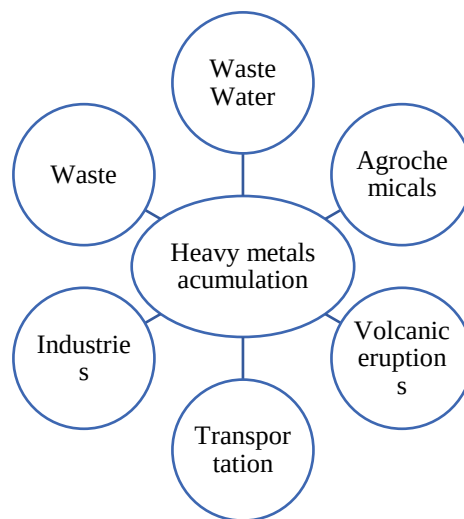
Heavy metals as Pb, Hg, Cd and As exceed the ranges of permissible limits established worldwide due to higher concentrations of anthropogenic and naturally contaminated waters



(Polo Bravo & Sulca Quispe, 2019). Some examples of maximum permitted levels of heavy metal contaminants are 0.05 mg/l of Arsenic, 0.005 mg/l of Cadmium, 0.015 mg/l of Lead, 0.002 mg/l of Mercury, 0.1 of Chromium, 0.05 mg/l of Selenium, 0.006 mg/l of Antimony (Rasheed et al., 2022). Currently, there is an increasing combination of agricultural practices concerning other anthropogenic activities, being an environmental concern (Chaoua et al., 2019). Different sources of metal accumulation are generated by industrial activities, transportation, volcanic eruptions, and use of agrochemicals, wastewater and waste (Figure 1).

Figure 1

Different responsible sources of the heavy metals accumulation in water and soil. Figure designed based on (Chaoua et al., 2019).



2.3 PHYTOREMEDIATION

Phytoremediation is a friendly biotechnology to the environmental, capable of preserving and restoring. It is highly profitable compared to other techniques of environmental remediation (Shah & Daverey, 2020), where plants accumulate heavy metals from contaminated soils and waters (Adhikari & Kumar, 2012; Cunningham et al., 1995). Aquatic macrophytes specific for phytoremediation have the potential to extract high levels of heavy metals in their roots, tolerate different metals, and have the physiological conditions to adapt to various environments (Bhat et al., 2022).

The ecotechnology named phytoremediation or plant-assisted remediation is considered one of the best for managing wastewater (Al-Ajalin et al., 2022). This technique remains a relatively new technology of mechanisms, which increases the effectiveness of phytoremediation



processes (Kristanti et al., 2023). It is a remarkable and ecological technique for removing various environmental contaminants from soil and water (Saini, 2021). Phytoremediation achieves the recovery of resources through a set of degradation, transformation, stabilisation and inactivation strategies of contaminants by plants, mainly through the activity associated with root systems (Caballero-Castaño et al., 2022).

Phytoremediation is one of the treatment technologies that use plants to remediate contaminants (Al-ajalin et al., 2020). Plants like “water lilies” and “water reeds” can help remove pollutants such as nitrogen and phosphorus effectively (Qu et al., 2023). In addition, factors like temperature, pH, oxygen, sunlight, beneficial microorganisms in the plant roots, and the concentration and type of contaminants present in the water can influence this treatment. It is necessary to keep these factors in mind to design effective phytoremediation systems (Qu et al., 2023), as floating wetland plants that obtain nutrients directly from the wastewater column due to their hanging roots. The hanging roots also help hasten nitrogen absorption and other pollutants (D. & R., 2023).

Regarding the species used in phytoremediation, excluding plants that preferentially accumulate metals, thus various root processes are described, protecting rhizomes and shoots from toxicity (Nabuyanda et al., 2019) from phytoremediation (phytoextraction, rhizofiltration, phytodegradation and phytovolatilisation). In any phytoremediation process, plants eliminate toxic substances and metal ions from wastewater (Saini, 2021). The process is based on the physical or metabolic interaction of contaminants with the root, the surrounding organic matter and the microorganisms that inhabit the rhizosphere (Caballero-Castaño et al., 2022).

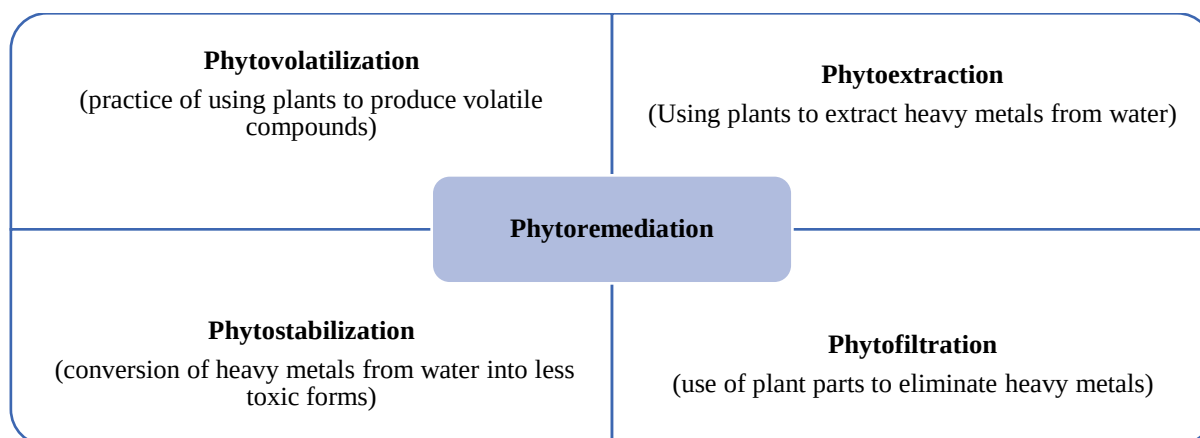
There are different phytoremediation methods, as phytoextraction, which uses plants for the translocation and accumulation of contaminants in their tissues, after absorbing them from soil or water (Jacob et al., 2018; Yan et al., 2020). On the other hand, phytostabilisation consists of the use of plants that contain heavy metals that stop mobility during the food chain process, reducing their accessibility to the ecosystem (Marqués et al., 2009; Wong et al., 2015).

Another process is phytovolatilisation, in which plants absorb toxins from the soil and water, transforming these harmful elements into less toxic but volatile states (Mahar et al., 2016). In contrast to phytofiltration itself is the practise of using roots, shoots or seedlings to eradicate impurities from soil or water, categorised as phytoextraction, rhizofiltration, phytostabilisation and phytodegradation (Khalid et al., 2017). Phytoremediation methods encompass phytoextraction, phytofiltration, phytostabilisation, and phytovolatilisation (figura 2).



Figure 2

Phytoremediation methods. Figure prepared based on information (Jacob et al., 2018).



Heavy metals (HMs) in the soil can cause contamination of surface and groundwater, extinction of useful microbes for agriculture, poor soil health, and a decrease in crop yields (Sarkar et al., 2017; P. K. Singh et al., 2018). Furthermore, metals accumulate in crops, posing a danger to ecological systems, including humans (Chai et al., 2018; Wang et al., 2020). According to Kiran Marella et al. (2020) a series of behaviours are responsible for the presence of HMs (Pb, Cd, Cr, Hg and Zn) in the aquatic environment (Rizwan et al., 2019).

Phytoremediation involves various applications of technologies for the water and soil decontamination depending on the type of contaminants and the capacity of aquatic macrophytes used for removal and degradation (Kong & Glick, 2017; Mendarte-Alquisira et al., 2021). Also, it is related to microorganisms that live in water (Mendarte-Alquisira et al., 2021) as endophytes, plant growth-promoting bacteria, arbuscular mycorrhizal fungi, filamentous fungi and dark-coloured septate fungi (Ullah et al., 2015). The phytoremediation process includes advantages and disadvantages depending on the technique used and among the most widespread techniques are phytoextraction, rhizofiltration, phytostabilisation, phytodegradation and phytovolatilisation (Table 1).

Table 1

Advantages and disadvantages of phytoremediation techniques

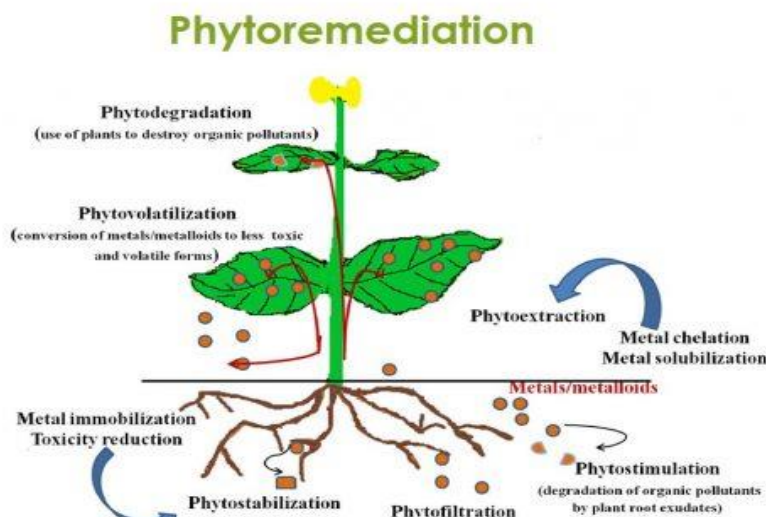
Techniques	Advantages	Disadvantages	References
Phytoextraction	Plants can effectively remove heavy metals and metalloids from soil and water. Additionally, they can absorb and store contaminants in their tissues, as seen in hyperaccumulator plants resistant to contaminants.	Soil and water remediation is a process that can take several years to achieve significant results. In addition, the extraction of contaminants is not always effective; therefore, plant species selection is essential for success.	(Sabir et al., 2015; Sarwar et al., 2017; Vamerali et al., 2010; Yang et al., 2020).



Rhizofiltration	Aquatic plants are hyperaccumulators and are effective in eliminating dissolved contaminants such as heavy metals from water. It could be used in various water systems, including groundwater and surface water. Phytoremediation can provide habitat and food sources for aquatic organisms.	It is not always effective for complex mixtures of contaminants. Plant species must be carefully selected to adapt to specific site conditions and types of pollution. There is a possibility of clogging of the plant's root systems.	(Vamerali et al., 2010; Mahar et al., 2016; Sarwar et al., 2017).
Phytostabilisation	Effective in reducing the mobility and bioavailability of heavy metal contaminants. Besides, contaminants are less likely to move through soil and water. Additionally, it would provide a long-term solution by preventing leaching of contaminants.	It is a slower process that can take several years to achieve the desired results. It has limited effectiveness for mobile contaminants or organic contaminants, as it requires maintenance and monitoring necessary to ensure plant growth and effectiveness.	(Vamerali et al., 2010; Sylvain et al., 2016; Y. Yang et al., 2020).
Phytodegradation	This process is a type of defence mechanism of plants against environmental pollutants. Hyperaccumulator plants modify, inactivate, degrade (phytodegradation) or immobilise (phytostabilisation) pollutants through the metabolism.	Limited effectiveness for highly persistent or complex organic compounds such as polychlorinated biphenyls (PCBs) and dioxins. It requires specific interactions between plants and microbes for optimal degradation such as those that occur in the rhizosphere (the root zone of plants).	(Vamerali et al., 2010; Mahar et al., 2016; Sarwar et al., 2017)
Phytovolatilisation	Hyperaccumulator plants absorb pollutants from soil and water, also transfer them to the aerial parts of plants and volatilise them into the air.	Vegetation growth could be affected by excess environmental toxicity and contaminants entering the food chain.	(Vamerali et al., 2010; Mahar et al., 2016; Sarwar et al., 2017)

Figure 3

Heavy metal adsorption mechanisms of aquatic plants. Figure prepared based on information (Vamerali et al., 2020).



Available in: <https://www.onlinebiologynotes.com/phytoremediation-classification-mechanisms-applications-and-limitations/>



Table 2

Plant species that accumulate heavy metals

Plant species	Heavy metals	Characteristics	References
<i>Lemna spp.</i>	Cd, Cr., Ni, Pb	Hyperaccumulator, accumulator, sensitive.	Al-Khafaji et al., 2018; Chaudhary & Sharma, 2019; Li et al., 2020; Q. Zhou et al., 2019).
<i>Azolla filiculoides</i>	Pb, Hg	Accumulator, moderately sensitive.	(Arshadi et al., 2017).
<i>Ceratophyllum demersum L.</i>	Cd, Pb, Cu	Hyperaccumulator, sensitive, moderate.	(Dogan et al., 2018; Matache et al., 2013).
<i>Typha angustifolia</i>	Zn, Cd, Pb	Moderately accumulating, moderately sensitive.	(Sricoth et al., 2018).
<i>Eichhornia crassipes</i>	Cr; Cu, Pb	Accumulator and tolerant.	(Eid et al., 2020; Sarkar et al., 2017; (Panneerselvam & Priya K, 2023).
<i>Typha latifolia</i>	Co	Vehicle emissions hyperaccumulator.	(Ahmad, 2022; Ray & Neogy, 2022).
<i>Potamogeton spp.</i>	Cu, Cd, Pb, Zn	Accumulator.	(Matache et al., 2013)
<i>Phragmites australis</i>	Zn, Mg	Accumulator through roots.	(Milke et al., 2020; Peltier et al., 2003).

Note: aquatic plant species friendly to phytoremediation

In the different phytoremediation processes (Figure 3) we have various species of plants that accumulate heavy metals, whose characteristics are hyperaccumulators, accumulators, sensitive and tolerant depending on plant species (Table 2).

The plants used in wetlands adapt to the conditions and characteristics of the new environment, developing in them, even in minimal oxygen conditions (Figure 4), because they have channels in their structure to transport the oxygen through their spaces roots (MARN, 2016).

Figure 4

Aeration channels of Aerénquima of enea (Typha ss.)



Fuente: Jesús Fernández, UPM



2.4 ARTIFICIAL WETLANDS

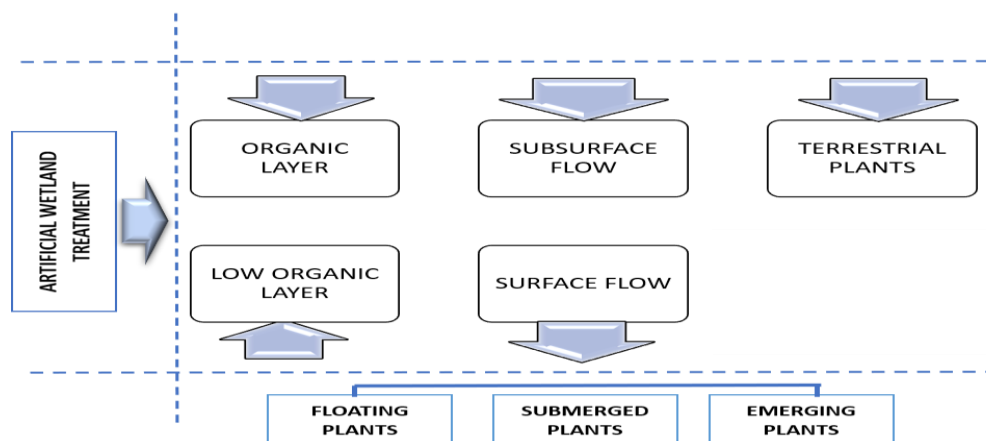
Constructed wetlands are a biotechnological process that has been used for more than five decades, designed and constructed to mimic processes that occur in a controlled environment (Vymazal & Březinová). They are systems with low operating and maintenance costs (Luna-Pabello & Aburto-Castañeda, 2014), capable of reducing contaminants when they receive wastewater and purifying it (Di Luca et al., 2019).

These engineering systems constitute a form of ecotechnology that uses biotransformation and mineralisation processes to reduce C, N, and P levels below the limits (Luna-Pabello & Aburto-Castañeda, 2014). Likewise, they propose two categories, one operates through an underground flow and the other in a surface flow (Kadlec & Wallace, 2008).

In the subsurface flow system, the water flows underground, ensuring that the water to be treated is not exposed to the environment (Langergraber et al., 2008) and allows the purification of high loads of organic contaminants. Surface flows are flooded systems with a water surface exposed to the environment with hydrophilic vegetation (Langergraber et al., 2008) used to treat artificial wetlands depending on the organic load and vegetation type (Figura 5).

Figure 5

Artificial wetlands treatment depending on the organic load and type of vegetation. Adapted figure (Luna-Pabello & Aburto-Castañeda, 2014).



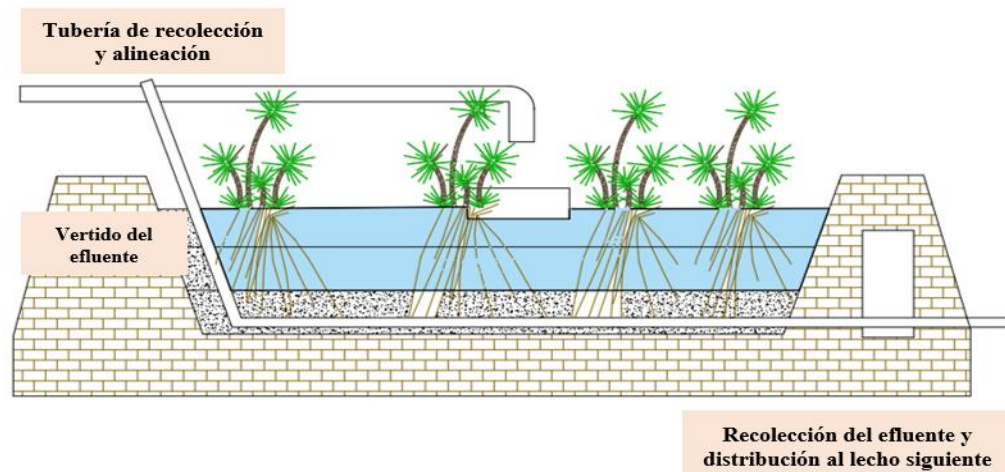
Wetlands with aquatic macrophyte disposition can assimilate a large amount of heavy metals, pharmaceutical products, etc. (Ávila et al., 2013) and perform an important role in wastewater purification (Bai et al., 2020). In addition, they are to create adequate conditions for the contaminant removal and absorption of nutrients and heavy metals (García-Valero et al.,



2019).

Figure 6

Phytoremediation technique of artificial wetlands. Figure made based on (Luna-Pabello & Aburto-Castañeda, 2014).



For an adequate design of an artificial wetland, it is crucial to know the associated problems, such as the water origin, quality and volume to be treated (Langergraber et al., 2008). Also, to prolong the useful life of artificial wetlands, it is indispensable to implement a pretreatment that facilitates the removal of suspended solids that are easy to settle (Luna-Pabello & Aburto-Castañeda, 2014). Prototype design of artificial wetlands as means of phytoremediation of wastewater treatment (Figure 6).

3 METHODOLOGY

The methodology adopted for this research includes data collection and compilation of existing information; regarding the different techniques related to wastewater treatment with artificial wetlands, these systems utilize natural processes involving vegetation, soil, and microbial activity to remove contaminants from water. More than 100 articles have been legally downloaded, and systematised in the database to paraphrase sentences and cite appropriately.



4 RESULTS AND DISCUSSION

Nutrient absorption by root or shoot are two dominant pathways for the growth of submerged macrophytes (Crossley, 2002; Rattray et al., 1991) such as the free-floating macrophytes *Lemna* spp, *Eichhornia crasipes*, *Myriophyllum spicatum* and *Potamogeton perfoliatus* that showed their potential phytoremediant for water purification of organic contaminants. Similarly, *Lemna minor*, *Wolffia globosa*, *Phragmites communis* can accumulate Cd, Zn, Pb, Ni, Cd and Cr as inorganic contaminants (Axtell, 2003; Baldantoni et al., 2004; Bhaskaran et al., 2013; Crossley, 2002; Rattray et al., 1991). Finally, *Azolla caroliniana* is a small aquatic fern that demonstrated that plants have the potential to purify waters contaminated by mercury and chromium (Bennicelli et al., 2004).

Water treatment using constructed wetlands (CW) is a common practice in many countries (Troitsky et al., 2019, Zhang et al., 2009). It offers a potentially cost-effective treatment system for a variety of water effluent types (Zhang et al., 2015, Malaviya y Singh, 2012) using aquatic plants that have shown to be crucial in removing heavy metals from wastewater (Kurniawan et al., 2021). For instance, floating wetlands that naturally emerge the root systems hydroponically to remove metals from water (Barco et al., 2021).

Wetland technology has received much attention as an alternative solution to conventional wastewater treatment systems because of its lower energy consumption, minimal maintenance requirements, and moderate capital cost (Shahid et al., 2020). This technique achieves water recovery through a combination of aquatic plants and microorganisms that are used to reduce nutrient concentrations in effluent wastewater and to inhibit eutrophication that results in oxygen depletion, odour generation and mortality of water species (Colares et al., 2020).

Finalmente, en la ciudad de Juliaca se han contabilizado más de 300 ladrilleras artesanales hasta el año 2014 las cuales están ubicadas en la vía de la salida a la ciudad de Arequipa (PRODUCE & PRAL, 2014), En cuanto al proceso de cocción del ladrillo se utilizan combustibles sólidos como: leña, carbón, neumáticos usados, plásticos recolectados u otros residuos; los cuales generan contaminantes atmosféricos (Soriano, 2012), dentro de los cuales el más predominante es el material particulado con una carga de contaminación de 1 557 toneladas por año (t/año) (MPSR, 2016). Los resultados de este estudio revelaron que actualmente, existen 312 ladrilleras artesanales en el sector de la Salida a Arequipa, del distrito de Juliaca, esto debido principalmente al incremento de la producción de estos materiales para la construcción.



5 CONCLUSION

Phytoremediation is an environmentally friendly technical choice because of its low cost to remediate water and soil contamination through methods of phytoextraction, rhizofiltration, phytostabilisation, phytodegradation and phytovolatilisation for organic contaminants, pesticides, oil waste, heavy metals, antibiotics, etc.

After phytoremediation, studies on the treatment and disposal of plant biomass are necessary to reduce waste disposal in landfills. The treated biomass has the potential to be converted into other bioresources such as biochar, biofuel and biogas. On the other hand, the application of modified biochar for artificial humidity can improve the removal of nitrogen and phosphorus. Consequently, reducing damage to aquatic organisms, with significant positive effects from biochar modification for the treatment efficiency (removal of organic matter, nitrogen and phosphorus) of horizontal subsurface flow (HSSF) gravel filters.

There are different phytoremediation methods such as phytoextraction, rhizofiltration, phytostabilisation, phytodegradation and hytovolatilisation for organic contaminants, pesticides, petroleum waste, heavy metals, pharmaceutical antibiotics, etc. Each of the elements has specific applications depending on the conditions of the place and the type of contaminants in an ecosystem.

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