Alternative methods for wastewater treatment. case study: phytopurification

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Abstract. Wastewater management is a major environmental and sanitary preoccupation for people around the world. impacted by urbanization and population growth, water management is becoming more complex than ever. Conventional treatment systems, such as wastewater treatment plants, are often expensive to build and to maintain, and can have negative impacts on the environment. given these challenges, it is essential to explore alternative wastewater treatment methods that are efficient, economical and ecologically sustainable. These new systems include phyto-purification, a method based on the treatment of wastewater by plants. The aim of our work is to describe the fundamental principles of phyto-purification, its advantages and disadvantages, its economic and environmental impact, and to project a case study on the implementation of this treatment method.

1 Introduction

Wastewater management is a major environmental and public health concern worldwide. With increasing urbanization, sustainable water management is becoming increasingly crucial. Conventional treatment systems, such as wastewater treatment plants, although effective, are often expensive to build and maintain. Moreover, they can have negative environmental impacts, particularly due to high energy consumption and the production of residual sludge [1].

In response to these challenges, it is essential to explore alternative wastewater treatment methods that are effective, cost-efficient, and environmentally sustainable. Plant-based treatment systems, or phytoremediation, emerge as a promising solution. This technique relies on the use of plants and associated microorganisms to degrade, stabilize, or eliminate contaminants present in wastewater.

Constructed wetlands, also known as planted filters or plant-based treatment areas, are a specific application of phytoremediation. These systems use basins filled with substrates such as gravel, sand, and soil, and are planted with aquatic vegetation capable of purifying water through their natural abilities to absorb, break down, and filter pollutants [2-4]. Constructed wetlands can treat a wide range of contaminants, including nutrients (nitrogen and phosphorus), organic matter, heavy metals, and pathogens.

Integrating constructed wetlands into urban or rural landscapes also offers additional benefits. Beyond their primary function of water treatment, they can serve as recreational areas, enhance local aesthetics, and promote biodiversity by creating habitats for various plant and animal species [5].

By exploring the fundamental principles of constructed wetlands, their operation, and practical application, this report aims to provide an in-depth understanding of this technology. The information presented can serve as a guide for institutions seeking to adopt similar approaches for sustainable and environmentally friendly wastewater management.

2 Principle of Wastewater Treatment by Plants

Wastewater treatment by plants, also known as constructed wetlands or phytoremediation, relies on the natural properties of plants to remove or reduce contaminants present in water. This process involves several mechanisms that work together to purify the water.

2.1 Root Absorption

Plant roots play a crucial role in absorbing nutrients and dissolved pollutants from the water. This mechanism includes two main stages[6-8]:

- Active Absorption: Plant roots actively absorb nutrients such as nitrogen (N) and phosphorus (P), which are essential for their growth. This process reduces the concentrations of these nutrients in the water, helping to prevent eutrophication in downstream water bodies.
- Passive Absorption: Roots also passively absorb water and dissolved contaminants, such as heavy metals and organic compounds. These substances are then transported into the plant tissues, where they can be stored or transformed.

2.2 Phytodegradation

Phytodegradation, or biotransformation, is the process by which plants break down organic contaminants into less harmful substances. Plant-produced enzymes play a key role in this mechanism[9]:

Enzymatic Degradation: Plant enzymes such as peroxidases and laccases break down complex organic compounds (such as pesticides, solvents, and hydrocarbons) into simpler and less toxic molecules.

Rhizodegradation: Microorganisms in the rhizosphere (the zone surrounding the roots) also contribute to contaminant breakdown. Root exudates (substances secreted by the roots) stimulate microbial activity, thereby enhancing the degradation of pollutants.

2.3 Phytostabilization

Phytostabilization is a process by which contaminants are immobilized in the soil, thereby reducing their mobility and bioavailability. This mechanism involves several steps:

Sequestration in the Soil: Plant roots help stabilize contaminants by adsorbing them onto the surface of soil particles or precipitating them into less soluble compounds.

Complex Formation: Some plants exude substances (such as organic acids) that form complexes with heavy metals, making them less mobile and less available to living organisms.

2.4 Phytovolatilization

Phytovolatilization is the process by which certain contaminants absorbed by plants are transformed into volatile compounds and released into the atmosphere through the stomata of the leaves. This mechanism is particularly effective for certain volatile elements such as mercury and selenium [10].
Transformation and Volatilization: Plants absorb contaminants in ionic or molecular form. Through their metabolic processes, they convert these substances into volatile compounds, which are then evaporated through the stomata, thereby removing pollutants from the aquatic environment [11].

2.5 Synergy Between Mechanisms

The different mechanisms of plant-based wastewater treatment often work synergistically, thereby enhancing the overall efficiency of the system. For example:
The presence of vegetation stimulates microbial biomass in the rhizosphere, which improves the degradation of organic contaminants.
Phyto-stabilization can reduce the number of pollutants available for root absorption or phytovolatilization, thus limiting the spread of contaminants.

2.6 Plant Selection for Treatment

Choosing the right plants is crucial for the effectiveness of phytoremediation-based wastewater treatment systems. Key selection criteria include [12, 13]:
- Pollutant Tolerance: The ability of plants to survive and grow in environments with high concentrations of contaminants.
- Absorption and Degradation Capacity: The plant's efficiency in absorbing, transforming, and/or volatilizing specific pollutants.
- Adaptability to Local Climate: The ability of plants to adapt to local climatic conditions (temperature, humidity, etc.).
- Rapid Growth and Biomass Production: Fast-growing plants that produce large amounts of biomass help maximize pollutant uptake and degradation.

Examples of commonly used plants in constructed wetlands:
- Reeds (Phragmites australis): Tolerant of a wide range of environmental conditions, effective in absorbing nutrients and heavy metals.
- Cattails (Typha spp.): Capable of absorbing and degrading a variety of organic and inorganic contaminants.
- Rushes (Juncus spp.): Effective in stabilizing pollutants and improving soil structure.

3 Preliminary Study and Implementation of the Constructed Wetland System

Before implementing a wastewater treatment system using constructed wetlands, a thorough preliminary study is essential. This crucial phase ensures that the designed system will be well adapted to local conditions and effectively meet treatment needs. Three main aspects are evaluated:
- Wastewater flow and volume: This involves measuring the daily volume of wastewater produced by permanent residents as well as temporary users (visitors, public facilities, etc.). This data is critical for properly sizing the basins and anticipating the hydraulic load to be treated.

- Wastewater quality: Physico-chemical and biological analyses are carried out to determine the composition of the wastewater. This includes concentrations of organic matter (BOD, COD), nutrients such as nitrogen and phosphorus, heavy metals (lead, copper, zinc, etc.), and pathogens (bacteria, viruses, parasites). These results guide technical decisions about the system (types of filters, plant species, residence time, etc.).
- Local climatic conditions: Average temperatures, annual rainfall, and frequency of frost periods directly influence plant growth, microbial activity, and water flow through the filters. These parameters are used to adapt the design to ensure maximum treatment efficiency year-round.

3.1 System Design

Based on the data collected, the constructed wetland system is custom-designed. This stage includes several major technical components:

- Sizing of the basins: Each component (pretreatment, settling, filtration, planted area) must be sized according to the estimated flow and pollutant load. The volume and depth of the basins are calculated to allow optimal water residence time, promoting sedimentation and biological treatment.
- Selection of plant species: The aquatic plants selected must not only tolerate local conditions but also have a high capacity to absorb pollutants and stimulate microbial activity. Reeds (Phragmites australis), cattails (Typha spp.), and rushes (Juncus spp.) are often preferred for their robustness and efficiency.
- Design of the hydraulic system: A gravity-fed circulation system is preferred, as it allows water to flow between the different components without using pumps, thus reducing energy consumption and maintenance. The water path is designed to maximize contact with the filtering substrates and plant roots.

3.2 Construction Phase

Once the design is validated, the construction of the system can begin, usually following these steps:

- Site preparation: This includes clearing the land, leveling it, and installing access roads and basic infrastructure (fencing, water supply, etc.).
- Construction of basins and filters: The basins are excavated, sealed (usually with a geomembrane liner), and then filled with layers of gravel, sand, and specific substrates that serve as a support for the plants.
- Planting: The selected plant species are introduced into the designated areas with a homogeneous distribution. The goal is to ensure sufficient plant cover from the early months, which is essential for effective treatment.
- Installation of the hydraulic network: Pipes, valves, overflow systems, and flow regulators are installed to control water movement between the different components of the system.

3.3 Commissioning and Startup Phase

The system is not brought into operation immediately. It is gradually commissioned to allow the plants to establish themselves and develop their root systems, which are vital to treatment performance. This phase includes:

- Initial testing: Wastewater is introduced gradually into the system. Regular testing is performed to monitor water quality at the outlet of each compartment and to identify any potential malfunctions.

- Technical adjustments: Based on test results, adjustments may be needed, such as modifying inflow rates, redistributing plants, or altering the water distribution system.
- Optimization: Once the system is stabilized, continuous monitoring is implemented to ensure optimal performance. This includes tracking plant growth, monitoring water quality, and performing preventive maintenance on the infrastructure.

4 Expected Results

4.1 Water Quality

The commissioning of the system is expected to have a significant impact on the quality of the treated water. The main anticipated outcomes include:
- Reduction of organic matter: Decrease in biochemical oxygen demand (BOD) and chemical oxygen demand (COD) concentrations by more than 90%.
- Nutrients: Reduction in total nitrogen and total phosphorus concentrations by 85% and 80%, respectively.
- Heavy metals and other pollutants: Effective absorption and degradation of heavy metals and micropollutants, with levels compliant with discharge standards.

4.2 Biodiversity

The constructed wetland system also contributes to the increase of local biodiversity. The main observations include:
- Flora: Introduction and growth of various aquatic plant species, promoting the diversification of local plant life.
- Fauna: Creation of favorable habitats for numerous animal species, including birds, insects, and amphibians, attracted by the wetland areas created by the system.

4.3 Cost and Maintenance

The operating and maintenance costs of plant-based filtration systems are generally lower than those of conventional treatment systems. The main maintenance tasks include:
- Plant Management: Regular monitoring and maintenance of the plants to ensure optimal growth and effective water treatment.
- Sludge Removal: Periodic removal of sludge accumulated in the settling basins to maintain system efficiency.
- Water Quality Monitoring: Regular analyses to verify that the treated water complies with current environmental standards.

5 Advantages and Disadvantages

Constructed wetlands offer several advantages, but also have some limitations. On one hand, they provide an eco-friendly solution by using natural processes to treat wastewater while reducing environmental impact. Their landscape integration enhances site aesthetics, blending seamlessly with the natural surroundings. Additionally, they promote biodiversity by creating habitats for various plant and animal species. From an economic standpoint, their operational and maintenance costs are lower than those of conventional treatment systems. However, this approach also has drawbacks. It requires significant space, often more extensive than compact artificial systems. Its effectiveness may vary depending on climatic conditions (extreme temperatures, droughts, or heavy rainfall), which can impact performance. Lastly, an adaptation period is required before the system reaches full filtration capacity, as the plants need time to establish themselves properly. Thus, while constructed wetlands offer a sustainable and visually appealing alternative, their implementation must consider these factors to ensure optimal performance.

6 Conclusion

Wastewater represents a major challenge in terms of environmental protection and sustainable management of water resources. It can be categorized according to its origin into three main types: domestic, urban, and industrial. In this study, we chose to focus on domestic wastewater, which mainly comes from households (greywater and blackwater). This type of wastewater is typically loaded with organic and inorganic pollutants, such as suspended solids, nutrients (nitrogen and phosphorus), pathogens, and various commonly used chemical substances.

The direct discharge of untreated wastewater into the natural environment poses a significant environmental risk. It can lead to the degradation of aquatic ecosystems, eutrophication of water bodies, and contamination of groundwater. To prevent these negative impacts, prior treatment is essential to eliminate or reduce pollutant concentrations to levels that comply with environmental standards.

Among the various existing treatment technologies, one of the most ecological and sustainable methods is the use of macrophyte-planted filters. This process, also known as constructed wetlands or phytoremediation, relies on the synergistic interaction between filter substrates (gravel, sand), aquatic plants (macrophytes), and the microorganisms present in the system. Together, they facilitate the degradation, transformation, and retention of pollutants found in wastewater, while also promoting local biodiversity.

As part of this study, we conducted an in-depth literature review on the functioning, performance, and limitations of macrophyte-planted filters. This bibliographic research allowed us to gain a better understanding of the mechanisms involved and to identify the factors influencing treatment efficiency. Based on this knowledge, we then designed an experimental study aimed at testing potential improvements to the system, particularly regarding plant selection, filter configuration, and operating conditions.

The results of this experiment will be presented in a future publication, in which we will propose concrete optimization strategies to enhance the performance and sustainability of phytoremediation systems in a domestic context.

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