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Comparative Assessment of Ornamental Plants in a Laboratory-Scale Constructed Wetland for TDS Reduction from Simulated Domestic Wastewater

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ABSTRACT

This study focuses on the effectiveness of a laboratory-scale horizontal subsurface flow built wetland (HSSFCW) intended for phytoremediation of simulated residential wastewater using two ornamental plant species: *Fittonia argyroneura* and *Syngonium podophyllum*. The system was built using a transparent acrylic tank coated with coarse gravel, fine gravel, sand, and clay to mimic natural subsurface wetland conditions and encourage root-zone interaction. Over a 5-day period, experimental procedures were carried out to assess the removal of Total Dissolved Solids. *Fittonia argyroneura* consistently reduced TDS more effectively than *Syngonium podophyllum*, and its effectiveness remained reasonably steady over time. *Syngonium podophyllum*, on the other hand, revealed a considerable rise in TDS content with prolonged contact durations, which might be attributed to organic leaching or microbial imbalance. Statistical analysis revealed substantial ($p < 0.05$) differences between the two systems. These findings emphasize the significance of plant species selection in improving engineered wetland performance. The system's modular architecture and low-cost materials make it suitable for decentralized wastewater treatment, especially in small-scale or rural applications. Overall, *Fittonia argyroneura* showed increased flexibility and promise for application in sustainable phytoremediation systems aimed at nutrient-rich residential effluents.

1. Introduction

Humanity is concerned about potential water-related disasters. Water pollution and shortage are significant global issues linked to population expansion and industrialization [1]. In 2015, the United Nations General Assembly established clean water and sanitation as one of its sustainable development goals (SDG). The UN warns that water shortages might cause 700 million people to be displaced by 2030. As of 2017, 2.2 billion people still needed clean drinking water [2]. Despite scientific advancements in wastewater resource recovery technologies, their widespread use in municipal wastewater treatment facilities (WWTPs) remains limited. There are both non-technical and technical explanations for this. Effective wastewater management is crucial for promoting sustainable urban growth [3]. Wastewater treatment dates back to 4000 B.C. when ancient Sanskrit and Greek cultures used charcoal filtration, light exposure, boiling, and straining to clean water. Pond-based technology dates back over 3000 years. Mitchell Lake, a 275 ha treatment pond with an average depth of 1.4 m, was formed near San Antonio, Texas, by accident in 1901 [4]. Municipal wastewater contains a diverse range of chemicals with high chemical energy levels. Understanding the energy potential of municipal wastewater is crucial for addressing the wastewater reclamation-energy nexus and establishing new process designs [5]. Researchers have developed innovative technologies to recover water, electricity, fertilizer, and other goods from municipal wastewater treatment facilities. This work is motivated by limited resource recovery potential and economic effectiveness, as well as the high energy needs and environmental impact of

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conventional treatment plant designs. Only a few technologies have been adopted, and transitioning from wastewater treatment plants to water resource facilities appears to be a long-term goal. This assessment provides decision-makers in water management utilities with information on the technical possibilities, market supply, and impediments associated with designing or redesigning municipal wastewater treatment processes for resource recovery [3]. Municipal wastewater is a promising renewable energy source due to its high energy content. Globally, approximately (330-390 km^3) of municipal wastewater (averaging 360 km^3) is generated annually, based on model simulations and historical data [5]. Traditional wastewater treatment plants have high construction and operational expenses, making them unsuitable for tiny settlements with limited resources [6]. Approximately 80% of wastewater is dumped into the environment untreated. Financial and technological constraints are hindering progress in addressing the global sanitation crisis. Many countries are experiencing increased demand for their limited water supplies. Higher water demand and limited supply cause over-abstraction and degradation in the availability and quality of water resources [7]. Untreated or insufficiently treated sewage discharge is one of the leading causes of global water pollution. Unchecked sewage discharge pollutes aquatic environments with diseases, organic debris, heavy metals, and nutrients. As a result, the quality of water in these natural reservoirs rapidly deteriorates, jeopardizing ecosystem health as well as the safety of water sources for human and agricultural use. Contamination of water bodies affects delicate aquatic ecosystems, resulting in a decrease in biodiversity and the loss of critical ecosystem functions. Municipal wastewater generally comprises suspended particles, biodegradable organic matter, nutrients, and pathogens. Domestic wastewater is divided into two types: greywater, which comes from bathing and washing, and black water, which includes feces, urine, and flush water discharged from toilets. Although black water accounts for a minor fraction of residential water, it includes the bulk of organic debris, nutrients, and pathogens [8]. CWs are a popular wastewater treatment method owing to their cost-effectiveness, low energy requirements, ease of operation, great efficiency in removing contaminants, and aesthetic appeal [9]. Estuarine salt marshes, known for improving water quality, are a prime example of how natural wetlands contribute to ecosystem protection [10]. The high volume of municipal wastewater released daily is a significant challenge for cities. Wetlands appear to offer a promising solution to this pressing problem. Wetlands, often known as biological filters, may effectively address environmental and water quality issues [11]. Constructed Wetland systems use physical, biological, and chemical processes to remove contaminants such as organics, nutrients, and trace elements, resulting in improved water quality [12]. Constructed Wetlands (CWs) are nature-inspired innovations that combine physical, biological, microbiological, and engineering components to successfully treat sewage and wastewater. These systems use filter media, wetland plants, and microbes to generate a microcosm of ecological balance, simulating the natural processes seen in wetland ecosystems. Filter media offer a habitat for beneficial microorganisms, which aid in the decomposition of organic matter and the removal of contaminants. Wetland plants improve the treatment process by absorbing nutrients and providing extra surfaces for microbial colonization on their roots, which promotes organic matter decomposition and nutrient uptake. Constructed wetlands (CWs) are needed to meet the UN's Sustainable Development Goals (SDGs), although their effectiveness in removing pollutants and their long-term viability remain unknown [13].

This study aims to design and implement a laboratory-scale phytoremediation system to evaluate the effectiveness of *Fittonia argyroneura* and *Syngonium podophyllum* in removing contaminants from simulated domestic wastewater, thereby assessing their potential for sustainable wastewater treatment applications.

2. Methodology

2.1 Design of the Phytoremediation System

The phytoremediation unit was designed as a laboratory-scale horizontal subsurface flow constructed wetland (HSSFCW), with overall dimensions of 80 cm in length and 40 cm in height, as illustrated in Figure 1. The system was constructed using a transparent acrylic tank to facilitate visual inspection and controlled experiments simulating domestic wastewater treatment.

The internal structure consisted of multiple substrate layers arranged from bottom to top as follows (see Figure 1):

- 10 cm Coarse Gravel Layer: Provides structural support and ensures effective drainage.

- 10 cm Fine Gravel Layer: Enhances filtration and microbial activity.
- 5 cm Sand Layer: Improves sediment retention and contributes to the filtration process.
- 10 cm Clay Layer: Acts as a medium for plant root development and nutrient adsorption.
- 5 cm Free Board: Prevents overflow and accommodates fluctuations in water level.

An outlet pipe was installed at the lower side of the tank to maintain horizontal flow and facilitate treated effluent collection. The system supports subsurface flow, which reduces surface exposure, limits odor generation, and prevents mosquito breeding.

Ornamental plant species—Fittonia argyroneura and Syngonium podophyllum—were planted in the clay layer, enabling their root systems to interact with the wastewater and contribute to pollutant uptake through biological and physicochemical mechanisms.

This design enables precise evaluation of phytoremediation performance under controlled laboratory conditions and allows comparative analysis of plant efficiency in treating synthetic domestic wastewater.

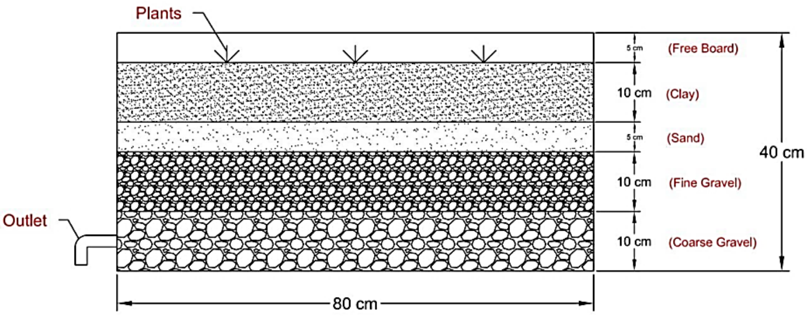

Figure 1. Schematic cross-sectional view of the laboratory-scale phytoremediation system showing substrate layers and flow configuration.

3. Results and discussion

The experimental findings showed that the laboratory-scale phytoremediation system was successful at treating simulated residence wastewater. *Fittonia argyroneura* and *Syngonium podophyllum* have shown ability to reduce total dissolved solids TDS. A comparison of the two systems revealed species-specific variations in pollution removal effectiveness. *Fittonia argyroneura* outperformed in terms of TDS reduction, showing that it has the capacity to promote microbial activity and particle entrapment within medium layers as shown in Figure 2. Environmental parameters such as light availability, temperature, and oxygen diffusion aided system performance but were kept constant to isolate the impact of plant species. Statistical analysis indicated substantial differences between the two systems ($p < 0.05$), confirming the validity of the comparison findings. Overall, the system design proved effective for laboratory-scale applications, and the findings suggest the potential scalability of such phytoremediation units for decentralized wastewater treatment in small communities or domestic settings.

These data indicate that plant species selection should be based on particular treatment aims. *Fittonia* may be more suited to nutrient-rich wastewater, whereas *Syngonium* does better with organic-rich effluents. Furthermore, the system's modular and scalable architecture makes it suitable for decentralized wastewater management, particularly in peri-urban or rural settings.

Figure 2 shows the fluctuation in Total Dissolved Solids (TDS) concentration with respect to contact duration, comparing the performance of two plant species (*Fittonia argyroneura* and *Syngonium podophyllum*) during a 5-day period. TDS concentrations were measured at contact durations of 24, 48, 72, 96, and 120 hours to determine the temporal efficacy of phytoremediation in a laboratory-scale system.

The graph shows that *Fittonia argyroneura* consistently outperformed *Syngonium podophyllum* in lowering TDS concentrations throughout the trial. At 24 hours, both plants had equivalent removal capacities (~230 ppm), indicating similar early response to the wastewater matrix. However, as the contact time increased, *Syngonium podophyllum*, TDS concentration rose sharply and gradually, reaching approximately 520 ppm at 120 hours, indicating a potential release of dissolved substances back into the system—possibly due to plant stress, organic leaching, or microbial imbalance in the rhizosphere.

Fittonia argyroneura had lower and more consistent TDS levels, with only a slight rise from ~210 ppm at 24 hours to ~270 ppm at 120 hours. This behavior represents *Fittonia argyroneura* improved physiological adaptability and potential ion absorption capability, as well as more effective root-zone microbial interactions that may contribute to long-term TDS uptake and transformation. From an engineering design standpoint, these findings emphasize the significance of species selection in system optimization. The high TDS concentration seen in *Fittonia argyroneura* system over time may impair effluent quality and necessitate extra treatment procedures, such as post-filtration or ion exchange. Meanwhile, *Syngonium podophyllum* shows excellent potential for use in low-tech, decentralized wastewater treatment applications, particularly in cases where salinity control is crucial. Several earlier research has supported the importance of decorative plants in improving pollution removal efficiency in artificial wetlands. For example, a study of horizontal subsurface flow wetlands planted with *Canna hybrids* and *Spathiphyllum blandum* found significant pollutant removal capabilities, including a reduction in Total Dissolved Solids (TDS), confirming the potential of ornamental species for use in decentralized wastewater treatment applications [14]. Other research findings, however, have shown that certain ornamental plants may contribute to elevated TDS levels through the exudation of dissolved organic compounds into the rhizosphere, a phenomenon that could lead to secondary pollution under prolonged retention times or in systems experiencing plant stress or microbial imbalance [15]. These findings support the current study's findings, notably the reported rise in TDS in systems planted with *Syngonium podophyllum*, and highlight the significance of plant species selection in maximizing wetland performance for long-term sustainability.

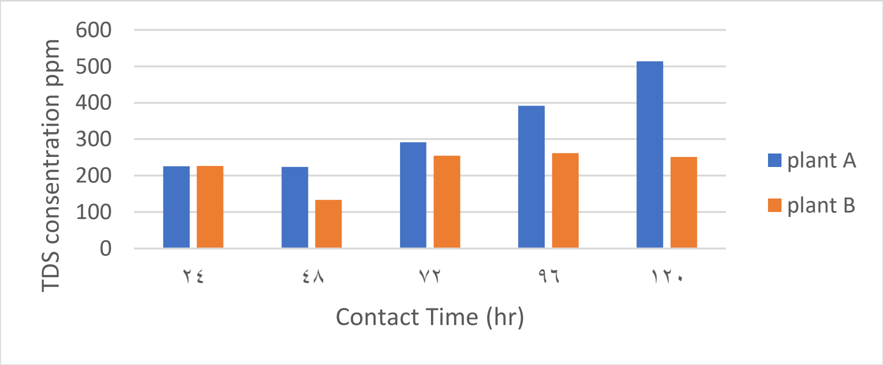

Figure 2. TDS Removal efficiency (A) *Fittonia argyroneura*, and (B) *Syngonium podophyllum*.

4. Conclusions

This study successfully demonstrated the design, implementation, and evaluation of a laboratory-scale horizontal subsurface flow constructed wetland (HSSFCW) system using two ornamental plant species: *Fittonia argyroneura* and *Syngonium podophyllum* to phytoremediate simulated domestic wastewater. The modular structure of the system, which was made up of layered substrates such as gravel, sand, and clay, offered a favorable environment for root growth, filtration, and microbial activity under regulated settings. The experimental results showed that both plant species contributed to TDS reduction throughout a 120-hour treatment period; however, *Fittonia argyroneura* consistently outperformed *Syngonium podophyllum*, resulting in lower and more stable TDS levels. This increased performance is due to improved root-zone microbial interactions, ion uptake efficiency, and physiological flexibility. In contrast, the observed increase in TDS levels in the *Syngonium* system with continuous exposure shows potential limitations in long-term treatment capability, possibly due to organic leaching or plant stress.

Statistical analysis ($p < 0.05$) revealed substantial differences between the two systems, highlighting the importance of plant species selection in improving phytoremediation efficacy. From an engineering standpoint, the system's clear and compact design enabled excellent performance monitoring and proved suited for small-scale or pilot applications.

While the system's modular and cost-effective design shows promise for decentralized wastewater treatment, particularly in small or rural towns, numerous limits must be considered. Long-term system stability may be jeopardized by variables like as biofouling, substrate clogging, and plant senescence, which can diminish treatment effectiveness over time. Furthermore, scaling to larger or more varied wastewater flows may need careful consideration of hydraulic retention time (HRT), plant density, and seasonal variation. Addressing these obstacles is critical for transferring such technologies from laboratory-scale experiments to field-level application.

Finally, the findings suggest the practicality and scalability of phytoremediation units based on *Fittonia argyroneura* for decentralized wastewater treatment, especially in resource-limited or rural areas. Future research should look at long-term system stability, plant regeneration cycles, and pollutant-specific removal efficiencies to improve design parameters and operational sustainability. Furthermore, the adoption of ornamental plant species such as Fittonia argyroneura adds value beyond pollution removal by providing aesthetic appeal and biodiversity advantages that are consistent with the concepts of urban green infrastructure (UGI). Their use in artificial wetlands within urban landscapes, such as parks, community gardens, and building-integrated systems, can promote sustainable water management, improve visual appeal, and contribute to urban ecosystem resilience

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