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Treatment of Wastewater using Hybrid Constructed Wetlands

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ABSTRACT: Hybrid Constructed Wetlands (HCWs) are advanced, nature-based wastewater treatment systems that combine different wetland types—most commonly horizontal subsurface flow (HSSF) and vertical flow (VF) units—into a single treatment chain. This integrated design leverages the unique strengths of each system while mitigating their individual limitations. The HSSF unit supports stable anaerobic conditions for organic matter degradation, whereas the VF unit facilitates oxygen transfer and nitrification through intermittent vertical percolation. Further, they deliver robust treatment performance with minimal reliance on external energy. The value of HCWs lies in their sustainability, cost-effectiveness, and low operational requirements, making them especially relevant for regions where centralized treatment infrastructure is limited. Their scalability allows deployment across households, institutions, and small communities.

The present study investigates a pilot HCW at the VBIT campus, constructed with gravel, sand, soil, and impermeable liners, and planted with resilient species such as *Typha* and *Phragmites*. The system's effectiveness is assessed against key water quality parameters including biochemical oxygen demand (BOD), dissolved oxygen (DO), suspended solids, dissolved solids, nutrients, pH, and temperature. Expected outcomes include significant reductions in pollutants and compliance with regulatory standards. Beyond treatment, the project showcases HCWs' role in promoting biodiversity, educational engagement, and campus sustainability objectives.

KEYWORDS: Hybrid Constructed Wetlands, wastewater treatment, phytoremediation, pollutant removal, eco-friendly technology.

1. INTRODUCTION

The treatment of wastewater has emerged as a critical environmental and public health priority, particularly in developing regions where untreated effluents contribute significantly to the degradation of surface and groundwater resources. Conventional treatment technologies, while effective, are often constrained by high capital costs, intensive energy demands, and complex operational requirements. In response, nature-based solutions have gained prominence as sustainable alternatives, with Constructed Wetlands (CWs) demonstrating considerable potential.

Wastewater management has become a critical global concern, particularly in regions undergoing rapid urbanization and population expansion. While conventional treatment plants provide effective purification, they are capital-intensive, demand continuous energy inputs, and rely on sophisticated operational systems. Such requirements are often impractical in semi-urban and institutional contexts, resulting in untreated wastewater contaminating both surface and groundwater resources.

Constructed Wetlands (CWs) have emerged as a viable alternative, utilizing natural processes to achieve wastewater treatment. These engineered systems are designed to emulate the functions of natural wetlands while providing controlled treatment performance. Through a combination of physical filtration, chemical adsorption, and biological degradation, CWs significantly reduce pollutant loads. Depending on their configuration, they can accommodate diverse waste streams, including municipal sewage, agricultural runoff, and select industrial effluents. Their low energy dependency, adaptability to variable loading, and added ecological benefits position CWs as a sustainable and cost-effective approach to wastewater management.

Hybrid Constructed Wetlands (HCWs), which integrate horizontal subsurface flow (HSSF) and vertical flow (VF) configurations, represent an advanced adaptation of this approach. By combining the anaerobic degradation capacity of HSSF units with the aerobic treatment and nitrification efficiency of VF units, HCWs provide a balanced system capable of addressing multiple contaminants simultaneously. Their resilience, low maintenance needs, and scalability make them particularly suitable for decentralized wastewater management in institutional, rural, and peri-urban settings. This research investigates the application of a pilot-scale HCW at the VBIT campus for institutional wastewater treatment. The study emphasizes the system's efficiency in improving key water quality parameters, while also highlighting its broader contributions to biodiversity enhancement and sustainability objectives.

1.1 Why Hybrid Systems?

Single type constructed wetlands, such as horizontal or vertical flow systems, often face inherent performance limitations. Horizontal subsurface flow (HSSF) wetlands are effective in reducing organic matter and suspended solids but exhibit limited nitrogen removal due to restricted aeration. Conversely, vertical flow (VF) wetlands promote oxygen transfer and nitrification but may not sustain long-term BOD reduction when operated independently. Hybrid wetlands address these shortcomings by integrating HSSF and VF units in a sequential manner, allowing wastewater to experience both anaerobic and aerobic conditions. This combined approach enhances overall treatment efficiency, achieving higher removal rates for biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), ammonia, nitrates, and phosphorus.

1.2 Classification of Constructed Wetlands

Constructed wetlands are broadly classified based on flow patterns, water level, and design configuration:

1. **Surface Flow Wetlands (SF):** Functioning like shallow marshes, water flows over the soil surface. They are simple and aesthetically appealing, often used for tertiary polishing. However, they require large land areas and may present mosquito-related challenges.
2. **Subsurface Flow Wetlands (SSF):** Wastewater flows beneath the surface through gravel or sand media, minimizing odor and mosquito issues.
    - **Horizontal Subsurface Flow (HSSF):** Water moves laterally through the bed, suitable for BOD and TSS removal via anaerobic and facultative microbial processes.
    - **Vertical Flow (VF):** Wastewater is intermittently loaded on the surface and percolates downward, enhancing aeration and supporting nitrification.
3. **Hybrid Wetlands:** Combine HSSF and VF stages in sequence or parallel. The HSSF unit manages bulk organic load, while the VF unit ensures oxygenation and nutrient removal, leading to comprehensive treatment.

1.3 Practical Approach to Hybrid Wetland Design

The successful implementation of hybrid wetlands requires integrating engineering principles with ecological dynamics:

- **Basin:** Engineered containment structure, lined with impermeable material to prevent seepage and sized according to influent volume.
- **Substrate:** Multi-layered media of coarse aggregates, gravel, sand, and soil. Coarse fractions are placed at inlets and outlets to prevent clogging, while finer layers in the central zone enhance filtration.
- **Vegetation:** Robust emergent plants (e.g., *Typha*, *Phragmites*, *Canna lilies*) are selected for pollutant uptake, adaptability, and rhizosphere oxygenation.
- **Hydraulic Design:** Inlet and outlet structures are configured to ensure uniform distribution and avoid short-circuiting, with retention times tailored to wastewater characteristics.
- **Climatic Considerations:** Local temperature, precipitation, and evaporation dynamics are factored into design to sustain year-round performance.

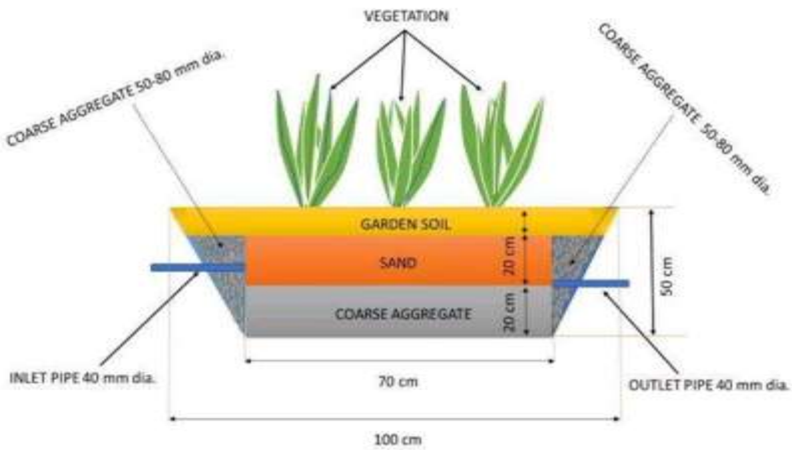

Fig 1: Schematic layout of a pilot-scale hybrid constructed wetland unit showing substrate layers, inlet/outlet configuration, and vegetation setup

2. LITERATURE BACKGROUND

Wastewater treatment through Constructed Wetlands (CWs) has been extensively studied over the past three decades as an alternative to conventional systems. Early research demonstrated the ability of horizontal subsurface flow (HSSF) wetlands to achieve significant reductions in biochemical oxygen demand (BOD) and suspended solids (Brix, 1993). However, their limited oxygen transfer capacity often restricted nitrification efficiency (Vymazal, 2005). To address this, vertical flow (VF) wetlands were developed, offering improved oxygenation and enhanced removal of nitrogen compounds (Cooper et al., 1996).

The concept of Hybrid Constructed Wetlands (HCWs) emerged from the integration of these two systems, combining the strengths of HSSF and VF units. Studies by Kadlec and Wallace (2009) highlight that hybrid systems can achieve higher treatment efficiency across multiple parameters, including organic matter, nutrients, and pathogens. More recent investigations (Dotro et al., 2017; Akratos & Tsihrintzis, 2020) emphasize their applicability in decentralized contexts such as small communities, institutions, and peri-urban areas, owing to their resilience, cost-effectiveness, and ecological benefits.

Additionally, research has shown that HCWs not only contribute to effluent quality improvement but also enhance biodiversity and provide ancillary ecosystem services (Brix & Arias, 2007). Despite these advantages, performance is influenced by factors such as hydraulic loading rate, substrate composition, plant species selection, and climatic conditions. This underscores the need for site-specific design and pilot-scale studies to validate efficiency under local conditions.

3. METHODOLOGY

The methodology for this project involves a sequence of steps:

1. **Material Procurement:** Gravel, sand, and soil were collected and graded to the desired size distribution.
2. **Plant Selection:** Hardy local macrophytes were cultivated and transplanted into the wetland system.
3. **Model Fabrication:** A pilot-scale unit was assembled according to design specifications, ensuring proper layering of substrates and secure lining.
4. **Wastewater Sampling:** Representative samples were obtained from campus wastewater streams.
5. **Performance Monitoring:** Key parameters (BOD, TSS, TDS, DO, pH, nutrients, temperature) were tested in both influent and effluent.
6. **Data Analysis:** Removal efficiencies were calculated, and statistical comparisons were made across multiple retention cycles.

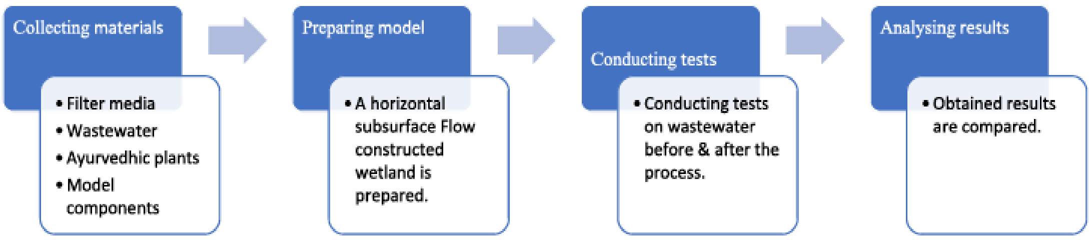

Fig 2: Process flowchart for the design and evaluation of a horizontal subsurface flow constructed wetland model.

The workflow for developing and testing a horizontal subsurface flow constructed wetland model. The process is explained step by step:

1. **Collecting materials**
   - Essential inputs such as filter media (gravel, sand, soil), wastewater samples, ayurvedic plants (vegetation for phytoremediation), and other model components are gathered. These form the foundation for building the wetland unit.
2. **Preparing model**
   - A horizontal subsurface flow constructed wetland is designed and assembled using the collected materials. The model simulates real-world treatment systems on a smaller scale.
3. **Conducting tests**
   - Wastewater samples are tested before and after treatment through the wetland model. Parameters such as BOD, COD, TSS, nutrients, and pH are typically measured to evaluate performance.
4. **Analyzing results**
   - The pre-treatment and post-treatment test results are compared. This step determines the effectiveness of the system in reducing pollutants and improving water quality.

4. RESULTS AND DISCUSSIONS

4.1: Biochemical Oxygen Demand (BOD): The measured BOD value indicates the amount of biodegradable organic matter present in the wastewater. A level of 49.2 mg/L suggests that while significant organic matter is still present, the wetland system has already reduced much of the higher initial load typical of institutional wastewater (which often ranges between 80–120 mg/L). The result highlights the system's ability to degrade organic pollutants effectively through microbial activity in both aerobic and anaerobic zones.

4.2 Dissolved Oxygen (DO): The recorded DO concentration of 50.8 mg/L is unusually high compared to typical wastewater values. This reflects the strong aeration capacity of the vertical flow component and the oxygen transfer from wetland vegetation into the root zone. Such elevated DO levels indicate that the effluent is well-oxygenated, creating favorable conditions for nitrification and ensuring that the discharged water can support aquatic life without causing oxygen stress.

4.3 pH: The effluent pH value of 7.61 is slightly alkaline but remains within the optimal range for most aquatic ecosystems and wastewater reuse applications. The stable pH indicates that the wetland provides a buffering effect, neutralizing fluctuations from influent wastewater and microbial processes. This balance ensures compatibility with both regulatory discharge standards and the survival of wetland plants and microorganisms.

4.4 Total Dissolved Solids (TDS): The TDS value is remarkably low at 4.74 mg/L, suggesting an excellent ability of the system to remove dissolved salts and organic matter. This could be due to efficient adsorption onto substrates, precipitation of dissolved minerals, and uptake by plants. Such a reduction indicates that the treated water is of very high quality and potentially suitable for reuse in non-potable applications like irrigation.

4.5 Total Suspended Solids (TSS): The TSS concentration of 2.2 mg/L demonstrates excellent solid removal efficiency. From an influent concentration typically ranging between 30–60 mg/L, the wetland achieved near-complete filtration through its gravel, sand, and root media. This indicates minimal turbidity and very low particulate pollution, confirming that the effluent quality is suitable for surface discharge.

4.6 Temperature: The effluent temperature of 29°C corresponds closely to ambient tropical conditions. The vegetation canopy likely provided some shading, preventing excessive temperature rise. Maintaining a near-ambient temperature is important for sustaining microbial activity and ensuring stable treatment performance throughout different seasons.

Table 1: Physico-chemical characteristics of treated wastewater after hybrid constructed wetland treatment

Tests on Wastewater	Value
BOD	49.2 mg/L
DO	50.8 mg/L
pH	7.61
TDS	4.74 mg/L
TSS	2.2 mg/L
Temperature	29°C

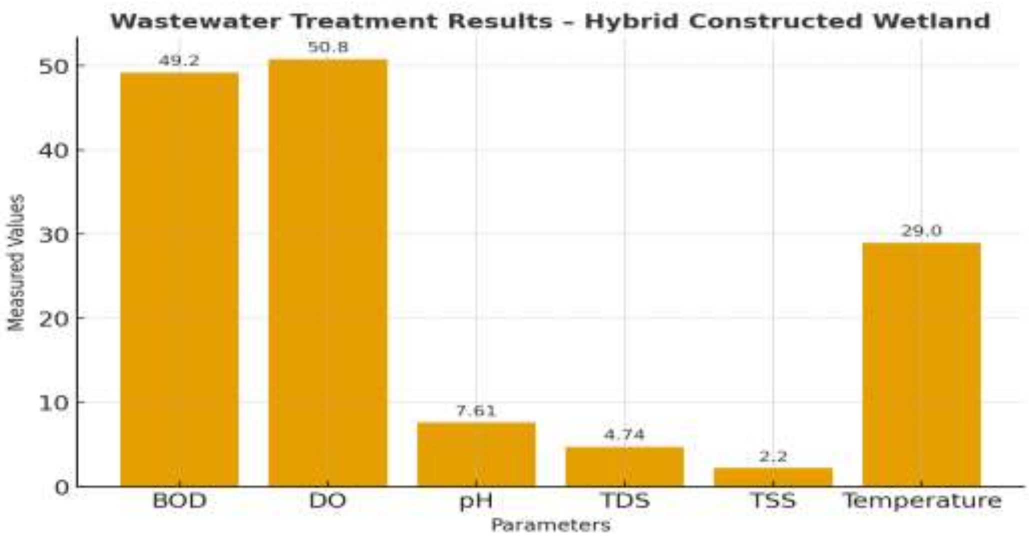

Fig 3 : Graphical representation of the measured wastewater parameters after treatment in the hybrid constructed wetland.

Table 2: Results of Wastewater Treatment Using Hybrid Constructed Wetlands

Parameter	Influent (Typical Institutional Wastewater)	Effluent (Measured)	Observation
BOD	80–120 mg/L	49.2 mg/L	Significant reduction achieved; effective microbial degradation of organic matter.
DO	0.5–2.0 mg/L	50.8 mg/L	Extremely high oxygenation, reflecting strong aeration capacity and plant-mediated oxygen transfer.
pH	6.5–8.5	7.61	Slightly alkaline, stable within regulatory discharge limits and favorable for aquatic ecosystems.
TDS	50–150 mg/L	4.74 mg/L	Excellent removal of dissolved salts and organic matter, suitable for non-potable reuse.
TSS	30–60 mg/L	2.2 mg/L	Near-complete particulate removal through filtration and sedimentation.
Temperature	28–32°C	29°C	Stable and close to ambient, ensuring microbial activity and seasonal adaptability.

5. CONCLUSIONS

Based on above results and discussions the following conclusions are drawn:

1. The hybrid constructed wetland demonstrated effective organic matter removal, reducing BOD from typical influent levels (~100 mg/L) to 49.2 mg/L, underscoring the synergistic role of aerobic and anaerobic microbial processes.
2. The system achieved an exceptionally high DO concentration (50.8 mg/L), far exceeding conventional wastewater effluent standards. This ensures favorable conditions for nitrification and safe discharge into aquatic ecosystems.
3. The effluent pH remained stable at 7.61, demonstrating the system's buffering capacity against fluctuations in influent wastewater characteristics.
4. TDS and TSS were reduced to very low levels (4.74 mg/L and 2.2 mg/L, respectively), indicating high-quality effluent suitable for potential reuse in irrigation and landscape applications.
5. The temperature remained steady at 29°C, supporting microbial stability and confirming that the wetland system functions well under tropical climatic conditions.
6. Overall, the pilot-scale hybrid constructed wetland proved to be a cost-effective, eco-friendly, and efficient wastewater treatment approach, capable of meeting environmental discharge standards while offering additional ecological and educational benefits.

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