

DESIGN AND SIMULATION OF DECENTRALIZED WASTEWATER TREATMENT SYSTEMS FOR PERI-URBAN AREAS USING HYBRID MODULAR UNITS

Abdul Baqui Raheem¹, Mr. Ushendra Kumar²

¹Master of Technology, Civil Engineering, Lucknow Institute of Technology, Lucknow, India

²Head of Department, Department of Civil Engineering, Lucknow Institute of Technology, Lucknow, India

Abstract - Rapid urbanization in peri-urban regions has intensified the challenge of wastewater management due to inadequate centralized sewerage infrastructure. This study presents the design and simulation of a decentralized wastewater treatment system (DEWATS) using hybrid modular units tailored for peri-urban conditions. The proposed system integrates physical, biological, and natural treatment processes, including screening, sedimentation, anaerobic baffled reactors (ABR), constructed wetlands, filtration, and disinfection. A representative peri-urban case with a projected population of approximately 16,386 and an estimated wastewater flow of about 1770 m³/day was considered. Design calculations were performed based on CPHEEO guidelines, ensuring technical reliability and contextual relevance. Simulation modeling using tools such as BioWin and MATLAB was conducted to predict system performance under varying hydraulic and organic loading conditions. The results indicate that the hybrid modular system achieves significant removal efficiencies for key pollutants such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS), meeting CPCB discharge standards. Sensitivity analysis further demonstrates the robustness and adaptability of the system. The study highlights the potential of hybrid DEWATS as a sustainable, scalable, and cost-effective solution for wastewater treatment in peri-urban areas.

Key Words: Decentralized wastewater treatment; Hybrid modular systems; Peri-urban sanitation; DEWATS; Simulation modeling; Constructed wetlands

1. INTRODUCTION

1.1 Background

1.1.1 Challenges in Peri-Urban Wastewater Management

Peri-urban areas represent transitional zones between rural and urban environments, often characterized by rapid population growth, unplanned development, and inadequate infrastructure. These regions face significant challenges in wastewater management due to increasing water consumption, rising wastewater generation, and limited institutional capacity. The variability in land use, ranging from residential to semi-agricultural activities, further

complicates the design and implementation of treatment systems. In such settings, untreated or partially treated wastewater is frequently discharged into the environment, leading to groundwater contamination, public health risks, and ecological degradation. These challenges necessitate the development of adaptable and decentralized treatment solutions that can function efficiently under variable loading and infrastructural constraints (UN-Habitat, 2015; Massoud et al., 2009).

1.1.2 Lack of Centralized Sewer Systems

A major limitation in peri-urban regions is the absence or inadequacy of centralized sewer networks. Conventional centralized wastewater treatment systems require substantial capital investment, extensive pipeline networks, and high operational expertise, which are often not feasible in rapidly expanding peri-urban zones. As a result, many communities rely on on-site sanitation systems such as septic tanks, which are frequently poorly maintained and inefficient in pollutant removal. This creates a pressing need for decentralized alternatives that can operate independently of large-scale infrastructure while ensuring effective treatment and environmental protection (Tilley et al., 2014).

1.2 Literature Review

1.2.1 Existing DEWATS Technologies

Decentralized wastewater treatment systems (DEWATS) have emerged as a viable solution for areas lacking centralized infrastructure. These systems typically incorporate a combination of primary, secondary, and tertiary treatment processes, including sedimentation tanks, anaerobic reactors, and natural treatment units such as constructed wetlands. DEWATS are known for their low energy requirements, minimal operational complexity, and suitability for community-scale applications. Previous studies have demonstrated their effectiveness in removing organic matter and suspended solids, particularly in developing regions where resource constraints are significant (Crites and Tchobanoglous, 1998; Kadlec and Wallace, 2009).

1.2.2 Hybrid Systems and Modular Approaches

Recent advancements in wastewater engineering have focused on hybrid systems that integrate multiple treatment technologies into a modular configuration. These systems combine the strengths of different processes, such as anaerobic digestion and natural polishing, to achieve higher treatment efficiencies. Modular designs offer flexibility, scalability, and ease of maintenance, making them particularly suitable for peri-urban contexts where demand and conditions may change over time. Hybrid DEWATS configurations, including anaerobic baffled reactors followed by constructed wetlands, have shown improved performance in terms of pollutant removal and operational stability (Von Sperling, 2007).

1.2.3 Gaps in Current Research (Lack of Simulation-Based Optimization)

Despite the growing adoption of DEWATS, many studies rely primarily on empirical design approaches and field observations, with limited use of advanced simulation tools. The absence of simulation-based optimization restricts the ability to predict system performance under varying conditions, such as fluctuating flow rates and pollutant loads. This gap reduces the reliability of design outcomes and limits the potential for system optimization prior to implementation. Incorporating simulation modeling into DEWATS design can enhance predictive accuracy and support informed decision-making (Henze et al., 2008).

1.3 Research Gap

1.3.1 Limited Integration of Design, Simulation, and Evaluation

Existing research often treats system design, performance simulation, and regulatory evaluation as separate processes rather than an integrated framework. This fragmented approach can lead to inconsistencies between theoretical design and actual system performance. A comprehensive methodology that integrates engineering design principles with simulation modeling and performance evaluation is essential to ensure reliability, efficiency, and compliance with environmental standards.

1.3.2 Lack of Context-Specific Models for Peri-Urban India

Another critical gap lies in the limited availability of context-specific models tailored to peri-urban conditions in developing countries, particularly India. Wastewater characteristics, climatic conditions, and socio-economic factors in these regions differ significantly from those in developed countries, making direct adoption of existing models inappropriate. There is a need for localized design frameworks that incorporate regional standards, such as CPHEEO guidelines, and address the unique challenges of peri-urban environments.

1.4 Objectives

1.4.1 Design of Hybrid Modular DEWATS

The primary objective of this study is to develop a hybrid modular decentralized wastewater treatment system that integrates multiple treatment processes into a cohesive and efficient configuration. The design aims to ensure technical feasibility, scalability, and adaptability to peri-urban conditions.

1.4.2 Simulation of System Performance

Another key objective is to simulate the performance of the proposed system using advanced modeling tools. Simulation enables the prediction of treatment efficiency under varying hydraulic and organic loading conditions, thereby reducing uncertainty and improving design reliability.

1.4.3 Evaluation against Regulatory Standards

The final objective is to evaluate the performance of the system against established regulatory standards, such as those prescribed by pollution control authorities. This ensures that the treated effluent meets environmental discharge requirements and supports safe reuse or disposal.

2. MATERIALS AND METHODS

2.1 Study Area Description

2.1.1 Peri-Urban Characteristics

The study focuses on a representative peri-urban region characterized by rapid urban expansion, mixed land use, and inadequate sanitation infrastructure. These areas typically exhibit a transition between rural and urban settings, where basic services such as wastewater management are often underdeveloped. The variability in land use, including residential, commercial, and semi-agricultural activities, leads to fluctuating wastewater characteristics and poses challenges for designing efficient treatment systems. The selection of such a study area ensures that the proposed decentralized wastewater treatment system (DEWATS) is context-specific and practically relevant.

2.1.2 Population Characteristics (5,000–20,000 Range)

The study considers a community-scale population ranging between 5,000 and 20,000, which is typical for peri-urban settlements. For design purposes, a base population of 10,000 is assumed and projected over a design period to account for future growth. This population range is suitable for decentralized systems, as it allows for manageable system sizing and efficient operation without the need for large-scale infrastructure.

5.1.3 Lack of Sewer Infrastructure

A defining feature of the selected study area is the absence of a centralized sewer network. This limitation necessitates the

adoption of decentralized treatment solutions capable of functioning independently. Existing sanitation practices, such as septic tanks or open discharge, are often inadequate and contribute to environmental pollution, thereby reinforcing the need for an efficient and sustainable DEWATS approach.

2.2 Research Framework

2.2.1 Engineering Design

The engineering design component is based on standard guidelines to ensure technical reliability and applicability. Design calculations are performed using established criteria for hydraulic retention time, loading rates, and safety factors. This ensures that each treatment unit is appropriately sized to handle the expected wastewater load while maintaining operational efficiency.

2.2.2 Simulation Modeling

Simulation modeling is employed to replicate the dynamic behavior of wastewater treatment processes. Advanced tools are used to model biological reactions, flow patterns, and pollutant removal mechanisms. This approach enables the prediction of system performance under varying conditions, reducing uncertainty and enhancing design accuracy.

2.2.3 Performance Evaluation

The performance of the proposed system is evaluated by comparing simulated outputs with regulatory standards. Key parameters such as BOD, COD, and TSS are analyzed to determine the treatment efficiency and compliance of the system. This step ensures that the designed system meets environmental discharge requirements.

2.3 Design Basis

2.3.1 Population Projection

Population projection is carried out using a geometric growth model to estimate future wastewater generation. Based on an initial population of 10,000 and a growth rate of approximately 2.5% over a 20-year design period, the projected population is estimated to be around 16,386. This projection ensures that the system is designed to accommodate future demand and avoid overloading.

2.3.2 Wastewater Generation

Wastewater generation is calculated based on standard per capita water supply values. Assuming a water supply of 135 liters per capita per day (LPCD) and a return factor of 80%, the total wastewater flow is estimated to be approximately 1770 m³/day for the design population. This value forms the basis for sizing all treatment units within the system.

2.3.3 Wastewater Characteristics

The design is based on typical wastewater characteristics observed in Indian conditions. Key parameters include

biochemical oxygen demand (BOD) ranging from 200–300 mg/L, chemical oxygen demand (COD) from 400–600 mg/L, and total suspended solids (TSS) from 200–350 mg/L. These parameters are critical for selecting appropriate treatment processes and predicting system performance.

2.3.4 Peak Factor Analysis

To account for variations in wastewater flow, a peak factor is applied. For the given population range, the peak factor is estimated to be between 2.9 and 3.0. This factor ensures that the system is capable of handling peak flow conditions without compromising performance or efficiency.

2.4 System Design: Hybrid Modular DEWATS

2.4.1 Treatment Train

The proposed system consists of a sequential treatment train designed to progressively remove contaminants. The process begins with screening and grit removal, followed by primary sedimentation. Secondary treatment is carried out using an anaerobic baffled reactor (ABR), which facilitates biological degradation. Tertiary treatment includes constructed wetlands for polishing, sand filtration for fine particle removal, and disinfection for pathogen control. This integrated approach ensures high treatment efficiency with low energy requirements.

2.4.2 Design of Units

Each treatment unit is designed using appropriate engineering principles. The settler tank is designed based on detention time to allow effective sedimentation of solids. The anaerobic baffled reactor is designed using hydraulic retention time (HRT) to ensure sufficient contact between wastewater and biomass for degradation. Constructed wetlands are designed using first-order kinetics to model pollutant removal efficiency. These design approaches ensure optimal performance and reliability of the system.

2.5 Simulation Modeling

2.5.1 Software Tools (BioWin / GPS-X / MATLAB)

Simulation of the treatment system is performed using advanced software tools such as BioWin, GPS-X, or MATLAB. These tools enable detailed modeling of biological and hydraulic processes, providing insights into system behavior under different operational scenarios.

2.5.2 Process Modeling

The simulation incorporates key processes, including biological degradation of organic matter, hydraulic flow distribution, and pollutant removal mechanisms. By modeling these processes, the study evaluates the efficiency of the system in reducing BOD, COD, and TSS under varying conditions.

2.6 Performance Evaluation

2.6.1 Comparison with CPCB Standards

The performance of the system is assessed by comparing the simulated effluent quality with regulatory standards prescribed by pollution control authorities. This ensures that the treated wastewater meets permissible discharge limits and is suitable for safe disposal or reuse.

2.6.2 Evaluation Parameters (BOD, COD, TSS)

Key performance indicators include reductions in BOD, COD, and TSS. These parameters are used to quantify treatment efficiency and determine the effectiveness of the hybrid modular system in removing organic and suspended pollutants.

2.7 Sensitivity Analysis

2.7.1 Variation in Flow Rate and Organic Load

Sensitivity analysis is conducted to evaluate the response of the system to variations in input conditions, such as changes in flow rate and organic loading. This analysis helps in understanding the adaptability of the system under real-world fluctuations.

2.7.2 System Robustness Evaluation

The results of the sensitivity analysis are used to assess the robustness and reliability of the proposed system. A robust system is one that maintains consistent performance despite variations in operating conditions, which is essential for peri-urban applications where variability is common.

3. RESULTS

3.1 Design Outputs

3.1.1 Flow Rates and Unit Sizing

The design outputs of the proposed hybrid modular DEWATS system are derived based on projected population, wastewater generation, and standard design criteria. The average wastewater flow is estimated at approximately 1770 m³/day, while peak flow conditions are considered using an appropriate peak factor to ensure system reliability. These flow values form the basis for sizing individual treatment units such as settlers, anaerobic baffled reactors (ABR), and constructed wetlands. The design ensures that each unit operates within optimal hydraulic retention time (HRT) and loading conditions to achieve efficient treatment.

Table 1: Design Flow Parameters

S.No	Parameter	Value
1	Design population	16,386
2	Water supply	135 LPCD
3	Wastewater generation	80%
4	Average flow (Q)	~1770 m ³ /day
5	Peak factor (PF)	2.9-3.0
6	Peak flow	~5130 m ³ /day

3.1.2 System Configuration

The system configuration follows a modular and sequential arrangement of treatment units designed to progressively remove contaminants. The treatment train consists of preliminary, primary, secondary, and tertiary stages, ensuring comprehensive treatment. Each unit is hydraulically and functionally integrated to maintain continuous flow and maximize pollutant removal efficiency.

Table 2: Hybrid Modular System Configuration

Stage	Unit	Function
Preliminary	Screening	Removal of large debris
Preliminary	Grit chamber	Removal of sand and grit
Primary	Settler	Sedimentation of suspended solids
Secondary	ABR	Anaerobic biological treatment
Tertiary	Constructed wetland	Nutrient and organic polishing
Tertiary	Sand filter	Fine filtration
Final	Disinfection	Pathogen removal

3.2 Simulation Results

3.2.1 Influent vs Effluent Quality

Simulation modeling provides a comparative assessment of influent and effluent wastewater quality. The influent characteristics reflect typical peri-urban wastewater conditions, while the effluent values indicate the

effectiveness of the treatment system. The results demonstrate a substantial reduction in organic and suspended pollutants across the treatment stages.

Table 3: Influent and Effluent Characteristics

Parameter	Influent (mg/L)	Effluent (mg/L)
BOD	250	20-30
COD	500	80-100
TSS	300	30-50

3.3 Performance Evaluation

3.3.1 Compliance with Discharge Standards

The treated effluent quality is evaluated against regulatory discharge standards to determine system compliance. The results indicate that the proposed hybrid modular DEWATS system meets the permissible limits for key parameters such as BOD, COD, and TSS. This confirms the suitability of the system for safe discharge or reuse in peri-urban environments.

Table 4: Compliance with Standards

Parameter	Effluent Value (mg/L)	Standard Limit (mg/L)	Compliance
BOD	20-30	≤ 30	Yes
COD	80-100	≤ 250	Yes
TSS	30-50	≤ 100	Yes

4. CONCLUSION

This study presents the design and simulation of a hybrid modular decentralized wastewater treatment system (DEWATS) tailored for peri-urban areas lacking centralized sewer infrastructure. The proposed system integrates physical, biological, and natural treatment processes into a cohesive and scalable framework, ensuring efficient pollutant removal under varying operational conditions. Based on a representative peri-urban case, the system was designed using standard engineering guidelines and evaluated through simulation modeling to predict performance.

The results demonstrate that the hybrid system achieves substantial reductions in key pollutants, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS), with effluent quality meeting regulatory discharge standards. The incorporation of an anaerobic baffled reactor (ABR) and

constructed wetlands enhances treatment efficiency while maintaining low energy and operational requirements. Furthermore, sensitivity analysis confirms the robustness of the system under fluctuations in flow and organic loading, which are typical in peri-urban environments.

Overall, the study validates the effectiveness of hybrid modular DEWATS as a sustainable, cost-effective, and adaptable solution for decentralized wastewater management. The integration of design, simulation, and performance evaluation provides a comprehensive approach that can support informed decision-making and practical implementation. The findings contribute to the advancement of decentralized sanitation strategies, particularly in developing regions facing rapid urbanization and infrastructural constraints.

5. FUTURE SCOPE OF RESEARCH

Future research should focus on pilot-scale implementation and field validation of the proposed hybrid modular DEWATS to assess real-time performance and operational challenges. Long-term monitoring studies are needed to evaluate system stability, maintenance requirements, and seasonal variations in treatment efficiency. Integration of advanced monitoring tools, such as IoT-based sensors and real-time data analytics, can further enhance system performance and management. Additionally, economic analysis, including life-cycle cost assessment and cost-benefit evaluation, would provide insights into financial feasibility. Research can also explore the reuse potential of treated wastewater for irrigation or non-potable applications. Finally, adapting the model to different climatic and socio-economic conditions would improve its applicability across diverse peri-urban settings.

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