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

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Abstract - *Rapid and unplanned expansion of peri-urban areas has intensified pressures on conventional centralized wastewater infrastructure, necessitating context-sensitive and scalable treatment alternatives. Decentralized wastewater treatment systems (DEWATS), particularly those configured as hybrid modular units, have emerged as promising solutions due to their adaptability, lower capital investment, and potential for phased implementation. This review critically synthesizes existing literature on the design principles, process integration strategies, and simulation approaches applied to hybrid modular decentralized systems in peri-urban contexts. The paper examines commonly adopted treatment combinations—such as anaerobic reactors, constructed wetlands, membrane units, and advanced polishing processes—and evaluates their performance in terms of pollutant removal efficiency, operational reliability, and resource recovery potential. Furthermore, it analyzes the role of process-based modeling, computational fluid dynamics, and system-level simulation tools in optimizing design parameters and predicting system performance under variable loading conditions. Key research gaps are identified, including the absence of standardized design frameworks, limited long-term field validation of simulation outputs, and insufficient integration of economic and sustainability assessment within modeling platforms. The review concludes by proposing a multidisciplinary framework that integrates modular engineering design, digital simulation, and sustainability metrics to enhance the implementation of decentralized wastewater solutions in rapidly urbanizing peri-urban regions.*

Key Words: **Decentralized wastewater treatment, Hybrid modular systems, Peri-urban sanitation, Process simulation, Sustainable infrastructure, Wastewater system design**

1. INTRODUCTION

1.1 Global Wastewater Crisis in Peri-Urban Transitions

1.1.1 Rapid Urban Expansion and Informal Settlement Growth

Accelerated urbanization, particularly in low- and middle-income countries, has resulted in the rapid spatial expansion of peri-urban areas characterized by mixed land use, informal settlements, and fragmented infrastructure networks. The United Nations estimates that nearly 56% of the global population currently resides in urban areas, with projections indicating continued growth, especially across Asia and Africa (UN DESA, 2022). Peri-urban zones often develop outside formal planning frameworks, leading to heterogeneous settlement patterns and inadequate sanitation provisioning. This transitional geography creates complex wastewater generation dynamics, including fluctuating hydraulic loads and variable organic concentrations, thereby complicating conventional infrastructure planning (Narain and Nischal, 2007).

1.1.2 Infrastructure Lag in Peri-Urban Fringes

The expansion of sewerage networks typically lags behind demographic growth due to financial, institutional, and topographical constraints. Centralized sewer systems require extensive capital investment, long conveyance pipelines, pumping stations, and coordinated governance structures. In peri-urban contexts, dispersed settlement morphology and uncertain land tenure further hinder network expansion (Massoud, Tarhini and Nasr, 2009). As a result, a significant proportion of wastewater in these regions remains untreated or partially treated, contributing to environmental degradation and groundwater contamination.

1.1.3 Limitations of Centralized Sewerage Expansion

Centralized wastewater treatment plants are designed under assumptions of stable influent characteristics, high population density, and economies of scale. However, peri-urban settlements often exhibit low-density clusters and inconsistent wastewater flows, rendering centralized extensions economically inefficient and technically impractical. Moreover, centralized systems lack flexibility to accommodate phased urban growth and are vulnerable to operational disruptions under variable loading conditions (Larsen et al., 2013). These structural mismatches underscore the need for decentralized and modular alternatives.

1.1.4 Environmental and Public Health Implications

Untreated wastewater discharge contributes to eutrophication, pathogen transmission, and deterioration of receiving water bodies. The World Health Organization reports that inadequate sanitation is directly associated with increased incidence of waterborne diseases, particularly in rapidly urbanizing regions (WHO, 2019). In peri-urban settings, where communities frequently rely on shallow groundwater and surface water sources, the environmental externalities of insufficient wastewater treatment are amplified, necessitating localized treatment solutions.

1.2 Emergence of Decentralized Wastewater Treatment Systems (DEWATS)

1.2.1 Conceptual Evolution of Decentralized Sanitation

Decentralized wastewater treatment systems (DEWATS) have evolved as context-responsive alternatives emphasizing localized treatment, reduced conveyance requirements, and community-level management. Early conceptualizations focused on small-scale anaerobic reactors and nature-based systems; however, contemporary DEWATS integrate multiple treatment stages to enhance removal efficiency and operational robustness (Tilley et al., 2014). The decentralization paradigm aligns with integrated urban water management principles, advocating for resource recovery and circularity.

1.2.2 Technical, Economic, and Governance Comparison with Centralized Systems

Technically, decentralized systems offer flexibility in hydraulic design, allowing treatment units to be tailored to specific influent characteristics and site constraints. Economically, they reduce capital-intensive infrastructure such as long sewer networks and pumping stations. Governance-wise, decentralized systems enable participatory management models and incremental scaling (Massoud, Tarhini and Nasr, 2009). However, challenges remain in terms of standardization, monitoring, and long-term maintenance.

1.2.3 Relevance to Peri-Urban Morphologies

Peri-urban environments are characterized by discontinuous development and spatial fragmentation, making modular decentralized systems particularly suitable. Localized treatment reduces dependency on centralized grids and enables phased implementation as settlements expand. Furthermore, decentralized configurations support water reuse for irrigation or groundwater recharge, which is critical in water-stressed regions (Larsen et al., 2013).

1.3 Rise of Hybrid Modular Treatment Units

1.3.1 Engineering Rationale for Hybridization

Hybridization refers to the integration of complementary treatment processes—such as anaerobic digestion, aerobic biofilm reactors, constructed wetlands, and membrane filtration—within a unified treatment train. Combining biological and physicochemical processes enhances pollutant removal efficiency, system resilience to shock loads, and nutrient recovery potential (Vymazal, 2011). Hybrid systems address limitations inherent in single-process configurations by leveraging process synergies.

1.3.2 Modularization and Scalability Principles

Modular design involves standardized, prefabricated units that can be replicated or expanded according to population growth. This approach enables phased capacity augmentation without substantial redesign. Modular systems also simplify installation, reduce construction time, and facilitate maintenance by isolating functional units. Scalability is particularly advantageous in peri-urban regions where demographic growth is incremental and unpredictable (Libralato, Ghirardini and Avezzù, 2012).

1.3.3 Integration of Biological, Physicochemical, and Advanced Treatment Units

Contemporary hybrid modular systems often incorporate anaerobic baffled reactors for primary treatment, followed by aerobic polishing units such as moving bed biofilm reactors or constructed wetlands, and advanced processes including membrane filtration or disinfection modules. Such integration enhances removal of biochemical oxygen demand (BOD), nutrients, suspended solids, and pathogens, enabling compliance with increasingly stringent discharge standards (Tchobanoglous et al., 2014).

1.3.4 Growing Adoption of Hybrid Modular Systems

The increasing emphasis on resource recovery, energy efficiency, and decentralized governance has accelerated adoption of hybrid modular units. Their adaptability to varying influent loads and reduced footprint compared to conventional systems make them attractive for peri-urban contexts where land availability and financial resources are constrained.

1.4 Role of Simulation in Modern Wastewater Design

1.4.1 Shift from Empirical Sizing to Model-Based Design

Traditional wastewater system design relied heavily on empirical guidelines and rule-of-thumb calculations. However, contemporary engineering practice increasingly employs mechanistic models based on activated sludge modeling (ASM) frameworks to simulate biological kinetics and system dynamics (Henze et al., 2000). Model-based approaches allow detailed prediction of effluent quality under varying operational conditions.

1.4.2 Predictive Tools under Variable Hydraulic and Organic Loading

Peri-urban wastewater streams often exhibit high variability in flow rate and pollutant concentration. Simulation tools enable sensitivity analysis, scenario testing, and performance optimization under fluctuating hydraulic retention times and organic loading rates. Such predictive capability is critical for ensuring resilience and reliability in decentralized modular systems (Rieger et al., 2012).

1.4.3 Simulation for Modular Optimization

In hybrid modular configurations, simulation facilitates optimization of unit sequencing, reactor sizing, aeration demand, and sludge production. Computational fluid dynamics (CFD) models further support hydrodynamic assessment of reactor performance, while integrated platforms enable techno-economic and environmental evaluation. The integration of digital modeling with decentralized system design represents a transformative step toward data-driven wastewater infrastructure planning.

1.5. Objective of this Review

- To systematically synthesize design principles
- To evaluate simulation methodologies
- To identify implementation gaps

2. CONCEPTUAL AND THEORETICAL BACKGROUND

2.1 Defining Peri-Urban Systems

2.1.1 Spatial Fluidity and Governance Ambiguity

Peri-urban systems represent transitional zones between rural and urban territories, characterized by spatial fluidity, socio-economic heterogeneity, and institutional fragmentation. These areas often fall outside formal municipal governance boundaries, resulting in regulatory ambiguity and inconsistent service delivery frameworks (Allen, 2003). Unlike planned urban centers, peri-urban regions experience incremental development driven by migration, informal housing expansion, and land-use conversion. This spatial dynamism complicates infrastructure planning, particularly for network-dependent systems such as sewerage and centralized wastewater treatment.

2.1.2 Infrastructure Heterogeneity

Infrastructure provision in peri-urban areas is typically uneven and fragmented. Households may rely on a mixture of septic tanks, pit latrines, open drains, and informal discharge pathways. Such heterogeneity leads to discontinuous wastewater conveyance and limited centralized collection efficiency (Narain and Nischal, 2007). The absence of standardized sanitation infrastructure increases environmental exposure risks and demands adaptable treatment configurations capable of functioning independently of large-scale sewer networks.

2.1.3 Wastewater Generation Patterns

Wastewater generation in peri-urban settings deviates from conventional urban assumptions of uniform flow and pollutant concentration. Variability arises from intermittent water supply, diverse income levels, and mixed land uses, including small-scale industries. Consequently, hydraulic loads fluctuate significantly on diurnal and seasonal bases. Organic and nutrient loads may also vary due to combined domestic and semi-industrial discharges (Libralato, Ghirardini and Avezzù, 2012).

Load variability poses operational challenges for biological treatment processes, as fluctuations in hydraulic retention time (HRT) and influent organic concentration can destabilize microbial communities. Additionally, many peri-urban clusters remain non-sewered, functioning as isolated sanitation units rather than integrated networks. Mixed domestic–semi-industrial effluents further increase chemical oxygen demand (COD) variability and introduce inhibitory compounds, necessitating robust and adaptable treatment design.

2.2 Engineering Framework of Decentralized Systems

2.2.1 Treatment Train Concepts

The engineering design of decentralized wastewater systems is structured around the treatment train concept, wherein wastewater passes sequentially through primary, secondary, and tertiary processes. Primary treatment typically involves sedimentation or anaerobic baffled reactors for solids removal. Secondary stages rely on biological oxidation processes, such as activated sludge or biofilm reactors, while tertiary units provide polishing through filtration or disinfection (Tchobanoglous et al., 2014). In decentralized configurations, treatment trains are often simplified yet optimized to maintain effluent compliance within constrained footprints.

2.2.2 Hydraulic Retention Time (HRT) and Sludge Retention Time (SRT)

Hydraulic Retention Time (HRT) represents the average duration wastewater remains within a reactor and is a critical parameter influencing organic matter degradation. Sludge Retention Time (SRT), also known as solids retention time, governs microbial population dynamics and treatment stability. Proper balancing of HRT and SRT ensures efficient biochemical oxygen demand (BOD) removal while minimizing sludge production. In decentralized systems, shorter HRTs may be adopted due to space constraints, necessitating intensified biological processes or hybrid configurations (Henze et al., 2000).

2.2.3 Organic Loading Rate (OLR) and Modular Scalability

Organic Loading Rate (OLR) quantifies the mass of biodegradable organic matter applied per unit reactor volume per day. Maintaining optimal OLR is essential to prevent process inhibition or underutilization of microbial capacity. In peri-urban applications, fluctuating OLRs require systems capable of absorbing shock loads without performance deterioration. Modular scalability addresses this challenge by enabling incremental addition of treatment units as population density increases. This modular paradigm supports phased infrastructure development and reduces upfront capital expenditure (Massoud, Tarhini and Nasr, 2009).

2.3 Hybridization in Wastewater Engineering

2.3.1 Functional Complementarity of Treatment Processes

Hybridization in wastewater engineering refers to the integration of complementary processes within a unified treatment framework. Biological, physicochemical, and advanced separation techniques are combined to exploit synergistic interactions. For instance, anaerobic reactors efficiently reduce organic load and generate biogas, while aerobic polishing units enhance nutrient removal. The theoretical basis for hybridization lies in process complementarity, where limitations of one treatment stage are offset by the strengths of another (Vymazal, 2011).

2.3.2 Anaerobic–Aerobic Coupling

Anaerobic–aerobic coupling is a widely adopted hybrid strategy. Anaerobic pretreatment reduces energy demand and sludge production, whereas subsequent aerobic processes ensure nitrification and improved effluent clarity. This configuration enhances overall removal efficiency while lowering operational costs compared to fully aerobic systems (Tchobanoglous et al., 2014). The sequential redox environment also improves resilience to hydraulic and organic shocks.

2.3.3 Integration of Nature-Based and Engineered Systems

Nature-based systems, such as constructed wetlands, are frequently integrated with engineered reactors to form hybrid modules. Wetlands provide tertiary polishing through sedimentation, plant uptake, and microbial transformation, while compact engineered units handle higher organic loads. Such integration balances ecological sustainability with process control, achieving footprint optimization and reduced energy consumption (Langergraber and Muellegger, 2005).

2.3.4 Membrane Integration and Theoretical Benefits

Membrane technologies, including membrane bioreactors (MBRs), are increasingly incorporated into decentralized hybrid systems to enhance effluent quality. Membrane separation ensures high suspended solids and pathogen removal, enabling water reuse applications. Theoretical benefits of hybrid modular systems include improved shock load resilience, spatial efficiency, and potential for resource recovery, such as biogas and nutrient recycling. These characteristics align with circular economy principles in water management (Larsen et al., 2013).

2.4 Simulation Paradigms in Wastewater Treatment

2.4.1 Mechanistic Models: Activated Sludge Model (ASM) Family

Mechanistic models are grounded in biochemical reaction kinetics and mass balance equations. The Activated Sludge Model (ASM) family, developed by the International Water Association, provides a standardized framework for simulating carbon oxidation, nitrification, and denitrification processes (Henze et al., 2000). These models allow engineers to predict effluent characteristics under varying operational scenarios and are widely implemented in commercial software platforms.

2.4.2 Empirical and Data-Driven Models

In contrast to mechanistic approaches, empirical models rely on regression analysis and statistical correlations derived from observed data. Recently, data-driven techniques such as artificial neural networks and machine learning algorithms have been applied to predict treatment performance under complex influent variability. These models are particularly useful where detailed kinetic parameters are unavailable, though they require extensive datasets for calibration (Rieger et al., 2012).

2.4.3 Computational Fluid Dynamics (CFD) Applications

Computational Fluid Dynamics (CFD) enables detailed analysis of hydrodynamics, mixing behavior, and mass transfer within reactors. CFD simulations support optimization of baffle placement, aeration distribution, and flow uniformity, thereby enhancing reactor efficiency. In modular systems, CFD assists in scaling reactor geometry without compromising hydraulic performance.

2.4.4 Digital Twin Concepts

Digital twin technology represents an advanced paradigm wherein real-time sensor data are integrated with dynamic simulation models to create virtual replicas of treatment systems. This approach enables predictive maintenance, operational optimization, and scenario forecasting. For decentralized modular systems operating under variable peri-urban conditions, digital twins offer a pathway toward adaptive and resilient infrastructure management.

3. LITERATURE REVIEW: DESIGN OF DECENTRALIZED SYSTEMS

3.1 Design Principles and Criteria

3.1.1 Treatment Targets and Effluent Standards

The design of decentralized wastewater treatment systems (DEWATS) is fundamentally governed by regulatory effluent standards and intended reuse applications. Treatment targets typically include removal of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), nutrients (nitrogen and phosphorus), and pathogens. International guidelines, including those for safe wastewater reuse, emphasize risk-based thresholds rather than uniform discharge values (WHO, 2016). Literature indicates that decentralized systems designed solely for organic removal may not consistently meet nutrient discharge limits unless supplemented with tertiary processes (Tchobanoglous et al., 2014). Consequently, recent studies advocate multi-stage treatment trains capable of achieving both carbon and nutrient removal while maintaining operational simplicity in peri-urban settings.

3.1.2 Physical Footprint and Modular Scalability

Land availability remains a decisive constraint in peri-urban wastewater infrastructure planning. Traditional stabilization ponds and large wetland systems require substantial land areas, which may be impractical in rapidly densifying fringes. To address this, modular compact reactors—such as anaerobic baffled reactors (ABRs), moving bed biofilm reactors (MBBRs), and membrane bioreactors (MBRs)—have been proposed to reduce spatial demand (Libralato, Ghirardini and Avezzù, 2012). Modular scalability enables phased expansion aligned with demographic growth, thereby minimizing overdesign and underutilization. However, literature highlights trade-offs between compactness and operational complexity, particularly in systems requiring mechanical aeration.

3.1.3 Cost and Resource Availability

Cost-effectiveness is a critical determinant of DEWATS adoption. Capital expenditures for decentralized systems are generally lower due to reduced conveyance infrastructure, but operation and maintenance (O&M) costs vary depending on technology choice. Passive systems such as constructed wetlands exhibit low energy demand but may incur higher land costs, whereas membrane-based units demand skilled maintenance and energy input (Massoud, Tarhini and Nasr, 2009). Studies emphasize the importance of lifecycle cost assessment rather than initial capital comparison alone. Additionally, local material availability and technical capacity significantly influence design feasibility in low-resource peri-urban contexts.

3.2 Hybrid System Configurations

3.2.1 Common Hybrid Combinations

Hybrid decentralized systems integrate complementary processes to enhance overall treatment efficiency. Frequently reported configurations include anaerobic digestion coupled with constructed wetlands, ABR followed by aerobic biofilm reactors, and membrane filtration integrated with biological treatment stages. Anaerobic–wetland combinations are widely documented for achieving substantial BOD and pathogen reduction with low energy demand (Vymazal, 2011). More advanced configurations incorporate membrane polishing units to achieve reuse-grade effluent suitable for irrigation or groundwater recharge. The literature suggests that hybridization improves process stability compared to single-unit systems, particularly under variable influent conditions.

3.2.2 Comparison of Design Approaches

Design approaches for hybrid systems vary between empirical sizing based on hydraulic loading rates and mechanistic design incorporating kinetic parameters. Nature-based hybrids often rely on surface loading criteria, whereas engineered reactors use parameters such as sludge retention time (SRT) and organic loading rate (OLR). Comparative analyses indicate that mechanistic approaches provide better predictive reliability but require detailed influent characterization (Henze et al., 2000). Conversely, empirical methods offer simplicity but may underperform under fluctuating loads typical of peri-urban systems.

3.2.3 Technical Advantages and Constraints

Hybrid systems offer enhanced resilience to hydraulic shock loads, improved nutrient removal through sequential redox environments, and reduced sludge production via anaerobic pretreatment. However, constraints include increased design complexity, higher monitoring requirements, and potential integration challenges between passive and mechanized components. Membrane integration, while ensuring superior effluent quality, introduces fouling management issues and elevated energy consumption. Thus, literature underscores the necessity of context-specific hybridization rather than universal configuration templates (Larsen et al., 2013).

3.3 Design Optimization

3.3.1 Parameter Selection

Optimization of decentralized systems involves careful selection of hydraulic retention time (HRT), sludge age, aeration intensity, and reactor volume. Sensitivity analyses demonstrate that small variations in OLR can significantly influence effluent quality, particularly in compact modular units (Rieger et al., 2012). Optimization frameworks increasingly employ simulation-based approaches to evaluate multiple operational scenarios prior to implementation.

3.3.2 Space Optimization and Modular Scalability

Space optimization strategies include vertical reactor design, stacked modular units, and integration of treatment units within community infrastructure layouts. Compact MBBR and MBR systems demonstrate reduced land footprint relative to conventional lagoons. Modular scalability enables incremental expansion, mitigating financial risk associated with overcapacity installation. Literature suggests that flexible design architecture is essential in peri-urban environments where settlement density evolves unpredictably.

3.3.3 Integration with Reuse Strategies

Decentralized systems are frequently designed with reuse objectives, such as landscape irrigation or non-potable urban applications. Integration with reuse strategies influences treatment targets, particularly pathogen reduction and nutrient polishing. Theoretical frameworks emphasize circular water management, where treated effluent and recovered nutrients contribute to local resource cycles (Larsen et al., 2013). However, successful reuse integration requires alignment with local regulations and public acceptance dynamics.

3.4 Case Studie

3.4.1 Asia

In South and Southeast Asia, decentralized anaerobic baffled reactors combined with polishing wetlands have demonstrated effective organic removal under high ambient temperatures. Case studies from India and Indonesia report BOD removal efficiencies exceeding 80%, with relatively low operational costs (Singh et al., 2015). However, nutrient removal performance remains variable without tertiary enhancement.

3.4.2 Sub-Saharan Africa

In African peri-urban settlements, simplified sewer networks connected to decentralized treatment modules have shown potential for incremental sanitation improvement. Studies indicate that hybrid systems integrating anaerobic pretreatment and maturation ponds achieve acceptable pathogen reduction under warm climatic conditions (Dodane et al., 2012). Nevertheless, long-term maintenance and institutional ownership challenges persist.

3.4.3 Europe and Latin America

In Europe, modular membrane-based decentralized plants have been implemented for small communities, achieving high effluent quality suitable for reuse. Latin American experiences highlight integration of decentralized treatment with agricultural reuse schemes, emphasizing nutrient recovery potential (Libralato, Ghirardini and Avezzù, 2012). Compared to developing regions, these systems benefit from stronger regulatory enforcement and technical capacity.

3.4.4 Comparative Insights Across Regions

Cross-regional comparison reveals that climatic conditions, governance structures, and economic capacity strongly influence design selection. Warm climates favor anaerobic processes due to enhanced microbial kinetics, whereas temperate regions rely more heavily on mechanized aeration systems. Resource constraints in developing regions drive preference for low-energy hybrid systems, while developed regions prioritize effluent quality and automation. The literature collectively indicates that no single configuration universally applies; rather, decentralized hybrid design must be tailored to local socio-technical contexts.

4. SIMULATION APPROACHES FOR SYSTEM DESIGN

4.1 Role of Simulation in DEWATS Design

4.1.1 Performance Prediction and Process Understanding

Simulation has become an integral component of modern decentralized wastewater treatment system (DEWATS) design, particularly where influent variability and operational uncertainty are pronounced. In peri-urban environments, wastewater characteristics fluctuate due to intermittent water supply, mixed land use, and seasonal changes. Mechanistic simulation enables prediction of effluent quality under varying hydraulic retention times (HRT), organic loading rates (OLR), and temperature conditions, thereby reducing reliance on empirical overdesign (Henze et al., 2000). By representing biological kinetics and mass balances explicitly, simulation tools support quantitative assessment of system robustness prior to implementation.

4.1.2 Design Optimization and Cost Evaluation

Beyond performance prediction, simulation facilitates multi-objective optimization involving treatment efficiency, energy consumption, sludge production, and lifecycle cost. Scenario-based modeling allows comparison of alternative configurations—such as anaerobic–aerobic coupling versus membrane integration—under projected growth conditions. Economic modules embedded within simulation platforms enable estimation of capital and operational expenditures, supporting evidence-based decision-making (Rieger et al., 2012). For decentralized modular systems, where incremental expansion is common, simulation helps evaluate phased capacity augmentation strategies and associated financial implications.

4.2 Modeling Tools and Software

4.2.1 Process-Based Models

Process-based simulation tools are grounded in mechanistic formulations of biochemical reactions, most notably the Activated Sludge Model (ASM) family developed by the International Water Association. Commercial software such as GPS-X, BioWin, and modeling environments like MATLAB / Simulink provide platforms for implementing ASM-based frameworks and customized hybrid system models. These tools enable dynamic simulation of carbon oxidation, nitrification–denitrification, and sludge kinetics. Their application to decentralized systems enhances predictive reliability, particularly when calibrated with site-specific influent data (Henze et al., 2000).

4.2.2 Empirical and Statistical Models

Empirical models rely on regression relationships derived from operational datasets, offering computational simplicity where detailed kinetic parameters are unavailable. Recent literature reports increasing application of machine learning algorithms for performance forecasting in small-scale treatment systems. While data-driven models demonstrate strong predictive capacity under known operating ranges, their extrapolation beyond training conditions remains limited (Rieger et al., 2012). In peri-urban contexts, where monitoring data may be sparse, empirical approaches often require cautious validation.

4.2.3 Computational Fluid Dynamics (CFD) for Unit Processes

Computational Fluid Dynamics (CFD) models simulate hydrodynamics, mixing patterns, and mass transfer within treatment reactors. In hybrid modular systems, CFD supports optimization of baffle placement, aeration distribution, and inlet–outlet configuration to minimize short-circuiting and dead zones. CFD analysis is particularly relevant for compact modular reactors where geometric configuration significantly influences treatment efficiency. Although computationally intensive, CFD enhances understanding of microscale flow behavior that cannot be captured by lumped-parameter kinetic models (Tchobanoglous et al., 2014).

4.3 Simulation of Hybrid Modular Units

4.3.1 Modeling Strategies for Modular Configurations

Hybrid modular units are typically simulated using compartmentalized reactor models, where each module (e.g., anaerobic reactor, aerobic biofilm unit, wetland cell) is represented as a discrete process block linked through mass balance equations. Sequential redox processes are modeled through staged kinetic parameters reflecting anaerobic and aerobic zones. Advanced simulations incorporate dynamic influent loading profiles to reflect peri-urban variability. Such modular modeling architecture allows evaluation of phased expansion scenarios without redesigning the entire system (Larsen et al., 2013).

4.3.2 Treatment Performance Validation

Validation of simulation outputs requires calibration against pilot-scale or field data. Studies demonstrate that mechanistic models can achieve acceptable prediction accuracy for BOD and ammonia removal when kinetic coefficients are adjusted to local temperature and influent conditions. However, pathogen removal and nutrient dynamics in nature-based modules often exhibit higher predictive uncertainty due to ecological complexity (Vymazal, 2011). Robust validation frameworks therefore combine short-term monitoring with long-term performance tracking.

4.3.3 Handling Parameter Uncertainty

Uncertainty analysis has gained prominence in decentralized system simulation due to variability in influent composition and operational practices. Sensitivity analysis identifies parameters exerting dominant influence on effluent quality, while Monte Carlo simulations quantify probabilistic performance ranges. Such approaches enhance design resilience by incorporating stochastic influent behavior rather than deterministic assumptions (Rieger et al., 2012).

4.4 Comparison of Simulation Tools

Process-based tools offer strong mechanistic insight and adaptability to hybrid configurations but require substantial calibration effort and technical expertise. Empirical models are computationally efficient and suitable for rapid assessment; however, they lack mechanistic interpretability. CFD provides detailed hydrodynamic visualization but is less practical for system-wide lifecycle analysis. In peri-urban contexts, the optimal approach often involves hybrid modeling—combining mechanistic core models with simplified economic and uncertainty modules. Suitability therefore depends on data availability, technical capacity, and design objectives.

4.5 Knowledge Gaps

4.5.1 Lack of Standardized Simulation Frameworks

Despite advances in wastewater modeling, standardized frameworks specifically tailored to decentralized hybrid modular systems remain limited. Most simulation platforms are optimized for centralized activated sludge plants, necessitating adaptation when applied to decentralized configurations. This gap restricts cross-comparison of performance results across studies and regions (Larsen et al., 2013).

4.5.2 Integration of Modularity in Models

Current models often treat treatment units as isolated reactors rather than expandable modules within evolving peri-urban settlements. Integration of modular scalability—where additional units dynamically alter hydraulic distribution and process kinetics—remains underdeveloped. Furthermore, coupling of process simulation with socioeconomic and governance variables is rarely addressed, limiting holistic system evaluation. Addressing these gaps is essential for advancing simulation-supported design of decentralized wastewater infrastructure.

5. PERFORMANCE EVALUATION AND SUSTAINABILITY METRICS

5.1 Technical Performance

5.1.1 Removal Efficiencies for Key Pollutants

Technical performance of decentralized wastewater treatment systems (DEWATS) is primarily evaluated through pollutant removal efficiencies, particularly biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), nutrients (nitrogen and phosphorus), and pathogenic indicators. Literature indicates that well-designed anaerobic baffled reactors (ABRs) can achieve BOD removal efficiencies between 65–85%, while hybrid systems incorporating aerobic polishing or membrane filtration often exceed 90% removal (Tchobanoglous et al., 2014). Nutrient removal performance, especially for total nitrogen, depends on the establishment of sequential aerobic and anoxic conditions enabling nitrification–denitrification cycles. Pathogen reduction is more variable and typically requires tertiary processes such as constructed wetlands, chlorination, or membrane separation to meet reuse standards (WHO, 2016).

5.1.2 Reliability and Resilience

Reliability refers to the system's ability to consistently meet effluent standards under normal operational conditions, whereas resilience reflects its capacity to withstand hydraulic and organic shock loads. In peri-urban contexts characterized by load variability, resilience is particularly critical. Hybrid systems demonstrate enhanced shock absorption due to staged treatment processes and distributed microbial communities (Vymazal, 2011). Studies show that anaerobic pretreatment reduces sudden organic spikes entering aerobic units, thereby stabilizing downstream processes. However, resilience also depends on adequate maintenance and operational oversight, which remain challenges in decentralized deployments.

5.2 Economic Evaluation

5.2.1 Capital, Operating, and Maintenance Costs

Economic sustainability of decentralized systems requires comprehensive evaluation of capital expenditure (CAPEX), operational expenditure (OPEX), and long-term maintenance costs. Decentralized configurations generally reduce capital costs associated with extensive sewer networks but may incur higher per-unit treatment costs due to smaller economies of scale (Massoud, Tarhini and Nasr, 2009). Passive systems such as wetlands have low energy demands but require land acquisition, whereas mechanized systems increase electricity consumption and technical maintenance requirements. Lifecycle costing approaches are increasingly recommended to capture the total economic implications over the system's design life.

5.2.2 Cost per Population Equivalent

Cost per population equivalent (PE) provides a standardized metric for comparing decentralized and centralized systems across scales. Literature suggests that decentralized systems become economically competitive in low-density or spatially fragmented settlements where centralized network extension is financially prohibitive (Libralato, Ghirardini and Avezzù, 2012). However, cost-effectiveness varies significantly depending on influent characteristics, regulatory requirements, and availability of local technical capacity. Economic modeling integrated with simulation tools can enhance accuracy in estimating cost per PE under variable growth scenarios.

5.3 Environmental and Social Sustainability

5.3.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) provides a comprehensive framework for evaluating environmental impacts associated with wastewater treatment systems, including greenhouse gas emissions, energy consumption, and material use. Comparative LCAs reveal that decentralized systems with anaerobic components often demonstrate lower carbon footprints due to reduced energy demand and potential biogas recovery (Larsen et al., 2013). However, membrane-based hybrid systems may exhibit higher embodied energy and operational electricity consumption. Incorporating LCA into design decision-making allows engineers to move beyond pollutant removal metrics toward holistic sustainability evaluation.

5.3.2 Resource Recovery: Water, Energy, and Nutrients

Modern sustainability paradigms emphasize wastewater as a resource rather than waste. Hybrid modular systems facilitate water reuse for irrigation, energy recovery through anaerobic digestion, and nutrient recycling via sludge management or effluent reuse (Tchobanoglous et al., 2014). In peri-urban agriculture-dependent communities, treated effluent provides a reliable irrigation source, contributing to local water security. Nutrient recovery, particularly phosphorus, aligns with circular economy principles and reduces dependency on synthetic fertilizers.

5.3.3 Social Acceptance and Governance

Technical and environmental performance alone does not guarantee long-term success. Social acceptance, institutional capacity, and governance structures significantly influence decentralized system sustainability. Community engagement enhances operational compliance and maintenance responsibility, particularly in shared modular facilities. Governance ambiguity in peri-urban areas, however, may hinder accountability and financial sustainability (Allen, 2003). Therefore, integration of participatory planning and clear regulatory frameworks is essential for durable implementation.

6. CRITICAL SYNTHESIS AND COMPARATIVE ANALYSIS

6.1 Comparative Summary of Designs and Simulations in Reviewed Literature

6.1.1 Design Philosophies Across Decentralized Configurations

A critical examination of the reviewed literature reveals two dominant design philosophies in decentralized wastewater treatment systems (DEWATS): passive nature-based configurations and engineered compact modular systems. Nature-based systems, such as constructed wetlands combined with anaerobic pretreatment, emphasize low energy input, operational simplicity, and ecological integration (Vymazal, 2011). In contrast, engineered systems incorporating moving bed biofilm reactors (MBBRs) or membrane bioreactors (MBRs) prioritize footprint minimization and high effluent quality, often at the expense of higher energy and maintenance demands (Tchobanoglous et al., 2014). The comparative evidence suggests that design choice is strongly context-dependent, influenced by land availability, effluent reuse objectives, and institutional capacity.

6.1.2 Integration of Simulation in Design Frameworks

The literature demonstrates variability in the depth of simulation integration within decentralized design processes. Some studies rely primarily on empirical sizing methods supported by limited steady-state modeling, whereas others employ dynamic process-based simulation grounded in Activated Sludge Model (ASM) kinetics (Henze et al., 2000). Advanced studies integrate scenario analysis to account for influent variability and phased expansion. However, the synthesis indicates that simulation is more extensively applied in engineered modular systems than in nature-based hybrids, where ecological complexity complicates mechanistic modeling. This uneven application of simulation tools highlights a methodological divergence within the field.

6.2 Cross-Tabulated Comparison of Modular Hybrid Systems

6.2.1 Technical Performance Comparison

Cross-analysis of hybrid modular configurations indicates that anaerobic–wetland systems achieve moderate to high organic removal with limited nutrient polishing unless supplemented by aerated stages. Conversely, anaerobic–aerobic–membrane combinations consistently demonstrate superior BOD, nitrogen, and pathogen removal efficiencies suitable for reuse applications (Libralato, Ghirardini and Avezzù, 2012). While membrane integration enhances effluent clarity, it introduces operational complexity related to fouling management and energy consumption. The comparative evidence suggests that high-performance configurations are particularly suitable where effluent reuse is mandated by regulation.

6.2.2 Spatial and Economic Trade-Offs

Spatial analysis indicates that nature-based hybrids require greater land area but exhibit lower operational energy requirements. Compact engineered modules minimize footprint, making them viable for dense peri-urban settlements; however, lifecycle cost assessments reveal higher OPEX due to mechanical components (Massoud, Tarhini and Nasr, 2009). Cross-tabulated evaluation across regions demonstrates that economic viability is strongly correlated with local electricity costs and availability of skilled operators. Therefore, spatial and economic trade-offs must be considered simultaneously during system selection.

6.2.3 Simulation Tool Applicability

Mechanistic modeling platforms show high predictive accuracy for activated sludge-based hybrid systems, particularly under dynamic loading conditions. However, for systems incorporating ecological components such as wetlands, empirical or semi-empirical approaches are often adopted due to challenges in parameter calibration (Rieger et al., 2012). This comparative insight underscores the need for hybrid modeling frameworks capable of integrating biological kinetics with ecological transformation processes. Current literature lacks standardized simulation structures that explicitly represent modular scalability and phased expansion.

6.3 Best Practices Identified

6.3.1 Context-Specific Hybridization

The synthesis of global case studies indicates that successful decentralized designs prioritize contextual alignment rather than technological uniformity. Warm climates favor anaerobic-dominated pretreatment due to enhanced microbial kinetics, while temperate regions may require intensified aeration to maintain process efficiency (Larsen et al., 2013). Best practice therefore involves tailoring hybrid combinations to climatic, regulatory, and socio-economic conditions.

6.3.2 Modular Scalability and Phased Implementation

Effective systems incorporate modular architecture that permits incremental expansion without interrupting ongoing treatment operations. This approach mitigates financial risk and aligns infrastructure growth with demographic changes. Literature consistently emphasizes the importance of flexible hydraulic distribution networks that can accommodate additional treatment units without extensive redesign (Tchobanoglous et al., 2014).

6.3.3 Integration of Simulation and Sustainability Metrics

A key insight from comparative analysis is that technically optimized systems do not automatically achieve sustainability objectives. Best practice frameworks integrate process simulation with lifecycle assessment and cost modeling to ensure balanced decision-making. Incorporating uncertainty analysis during the design phase enhances resilience against variable influent conditions and governance instability (Henze et al., 2000).

7. CONCLUSION

This review critically examined the design and simulation dimensions of decentralized wastewater treatment systems (DEWATS) employing hybrid modular units for peri-urban applications. The synthesis demonstrates that decentralized configurations offer structural advantages in spatially fragmented and infrastructure-deficient contexts, particularly where centralized sewer extension is economically or technically impractical. Hybridization—through integration of anaerobic, aerobic, nature-based, and membrane processes—enhances pollutant removal efficiency, operational resilience, and adaptability to hydraulic and organic load variability. Simulation tools grounded in mechanistic modeling have emerged as essential instruments for performance prediction, optimization, and lifecycle cost evaluation, although their application remains uneven across system typologies. Comparative analysis indicates that system suitability is strongly context-dependent, influenced by climatic conditions, land availability, regulatory standards, and institutional capacity. Importantly, sustainability assessment must extend beyond technical efficiency to incorporate lifecycle environmental impacts, economic feasibility, and governance frameworks. The review highlights the need for integrated design approaches that combine modular engineering principles with robust simulation and sustainability metrics. Advancing standardized modeling frameworks and incorporating uncertainty analysis will be pivotal in supporting scalable and resilient wastewater solutions for rapidly urbanizing peri-urban regions.

7.1. Limitations of the Review

This review is limited by its reliance on published peer-reviewed literature, which may underrepresent operational data from small-scale or informally implemented decentralized systems. Variability in reported performance metrics, climatic conditions, and influent characteristics constrained direct quantitative comparison across case studies. Additionally, differences in modeling assumptions and calibration procedures limited systematic evaluation of simulation tool accuracy. The review focused primarily on technical and sustainability dimensions, with less emphasis on detailed socio-political or legal analyses that influence implementation outcomes. Finally, rapid technological evolution in digital modeling and hybrid treatment configurations may render some findings time-sensitive, necessitating ongoing updates as new empirical evidence emerges.

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