Performance Modeling and Field Validation of Decentralized Wastewater Treatment Systems in Semi-Arid Azerbaijan: A Pilot Case Study

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Abstract

Safe and sustainable sanitation remains a critical challenge in rural and semi-arid regions lacking centralized wastewater infrastructure. This study assesses the environmental impacts of uncontrolled domestic wastewater discharge and introduces a decentralized treatment and performance modeling framework for the Shamakhi-Gobustan region of Azerbaijan. Field analyses detected elevated levels of BOD (18-25 mg/L), COD (45-70 mg/L), nitrates (up to 65 mg/L), and coliform bacteria (>100,000 MPN/100 mL), all exceeding WHO standards. To mitigate these risks, a pilot system integrating a sedimentation tank, anaerobic baffled reactor, constructed wetlands, and solar-powered pumps was implemented in Tekle village. The system achieved average pollutant reductions of 85% for BOD, 70% for COD, and substantial removal of nitrates and coliforms. A mass balance-based model was developed to evaluate treatment efficiency, with outputs closely matching observed data ($R^2 = 0.94$, RMSE = 4.2 mg/L COD), confirming reliability and scalability. This combined field validation and modeling approach offers a transferable framework for improving sanitation in other water-scarce regions. Beyond the local case, the findings advance Sustainable Development Goals (SDG 6: Clean Water and Sanitation; SDG 13: Climate Action) by demonstrating a practical, cost-effective, and climate-resilient pathway for rural wastewater management.

Keywords: decentralized wastewater treatment, performance modeling, constructed wetlands, anaerobic baffled reactor, rural sanitation, SDG 6, SDG 13.

1. Introduction

Access to safe and sustainable sanitation remains a critical challenge for rural and semi-urban communities worldwide. According to the WHO and UNICEF Joint Monitoring Programme, over 1.7 billion people still lack access to safely managed sanitation services, the majority in rural and peri-urban areas [1, 2]. The absence of wastewater treatment infrastructure leads to groundwater pollution, local environmental degradation, and significant public health risks [3, 4].

Figure 1 illustrates global disparities in sanitation service levels, underscoring the urgent need for decentralized and context-specific solutions, particularly in low- and middle-income countries.

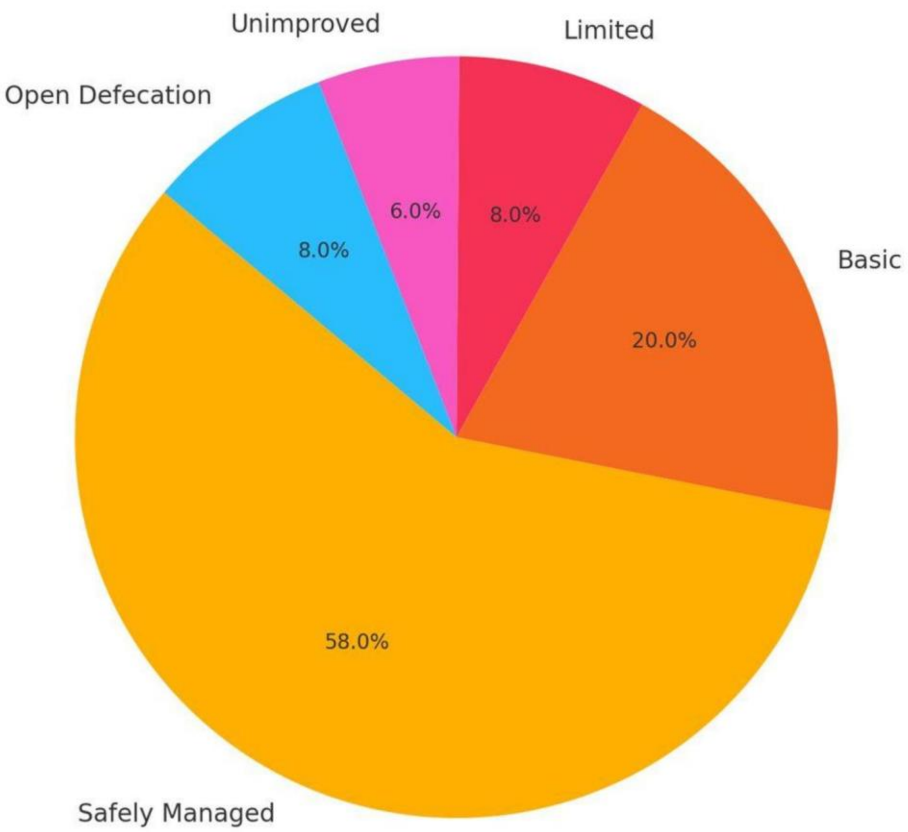

Figure 1. *Global Sanitation Service Levels (WHO/UNICEF JMP, 2023).*

Distribution of the global population according to sanitation service levels based on the WHO/UNICEF Joint Monitoring Programme 2023 report. Categories include safely managed, basic, limited, unimproved, and open defecation services.

Traditional centralized wastewater treatment systems require substantial capital investment and high operational expenditures, making them impractical for rural areas with dispersed populations and limited resources [6, 7]. Consequently, decentralized wastewater treatment systems (DEWATS) have gained prominence as sustainable alternatives adaptable to geographic, climatic, and socio-economic conditions [8, 9]. For instance, DEWATS pilots in India and Turkey achieved BOD removal rates of 70-80% under similar rural conditions, demonstrating their feasibility. In recent years, performance modeling has increasingly been incorporated into DEWATS planning, enabling quantitative assessment of pollutant removal and supporting optimization and scalability [9, 10].

The Shamakhi-Gobustan region of Azerbaijan exemplifies a setting where centralized wastewater infrastructure is virtually absent. Villages typically rely on septic pits or direct discharge into land and waterways [6, 12]. The shallow groundwater table (2-8 m) heightens contamination risks from untreated wastewater [4, 29]. Assessments by the Azerbaijan State Water Resources Agency (ADWRA) and the Ministry of Ecology and Natural Resources indicate that about 65% of rural settlements lack formal wastewater management systems [28, 32]. While decentralized systems have been piloted in other semi-arid countries, this study represents the first attempt in Azerbaijan to integrate DEWATS with performance modeling and solar-powered operation, addressing both groundwater contamination risks and national sanitation policy gaps.

This research evaluates the environmental impacts of unregulated domestic wastewater discharge in the Shamakhi-Gobustan region and tests the viability of decentralized treatment solutions. A hybrid pilot system was implemented in three villages - Tekle and Jangi (Gobustan District) and Chukhuryurd (Shamakhi District) - combining sedimentation, anaerobic baffled reactors, constructed wetlands, and solar-powered pumps.

Emerging research highlights additional challenges, including pharmaceuticals and hormones in wastewater, which require advanced treatment [38]. Bioremediation methods, such as Ganoderma-based fungal treatments, have also shown promise against persistent pollutants [39]. Moreover, pharmaceuticals have been found to accumulate in crops irrigated with reclaimed wastewater, raising food security concerns [44]. Although this study does not directly target pharmaceuticals, these findings reinforce the broader relevance of sustainable and adaptive treatment frameworks.

Despite global progress in DEWATS deployment, few studies have combined field monitoring with mass-balance modeling in semi-arid regions to assess scalability under real rural conditions. To the best of our knowledge, this is the first pilot-scale study in Azerbaijan to couple decentralized wastewater treatment with performance modeling and solar-powered operation. The central research question is: How can decentralized wastewater treatment systems be effectively modeled, validated, and scaled in semi-arid, infrastructure-limited regions?

Beyond the local case, the findings provide a transferable framework for sanitation in water-scarce and data-scarce contexts. By aligning technical design with performance modeling, the study offers practical insights for semi-arid regions worldwide and supports global sustainability targets, particularly SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) [5, 9, 21, 32]. Recent advances in wastewater treatment - such as membrane-based processes for pharmaceuticals [40] and bioremediation approaches for petroleum hydrocarbons [41] - further illustrate the growing trend toward sustainable technologies, underscoring the timeliness of this work.

2. Literature Review

Access to safely managed sanitation remains a pressing global and regional concern [1]. According to UN-Water and the World Health Organization, more than two billion people worldwide still lack access to safely managed drinking water and sanitation services [2]. This gap is especially severe in low-income and rural areas, where infrastructure development is delayed or insufficient [3]. In Azerbaijan, challenges are particularly acute in rural areas of the Shamakhi and Gobustan districts, where the absence of centralized wastewater systems contributes to environmental degradation and public health risks [6, 12].

Decentralized wastewater treatment systems (DEWATS) have gained recognition as sustainable alternatives to centralized approaches [11]. They are characterized by lower capital and operational costs, minimal energy requirements, and adaptability to diverse climatic and geographical conditions [5, 7, 8, 18]. DEWATS are particularly suitable for rural and peri-urban areas, where dispersed populations and funding constraints make centralized networks impractical [6, 8, 17].

Within decentralized systems, pre-treatment methods such as bioflocculation have been explored to enhance energy efficiency and support downstream treatment, particularly for rural greywater [14]. Membrane-based technologies such as nanofiltration (NF) and reverse osmosis (RO) have also been tested for nutrient and pathogen removal, though limited by high energy and maintenance costs [15]. Recent studies further highlight the potential of nanofiltration membranes for removing pharmaceuticals from sewage effluent, underscoring the wider applicability of membrane-based DEWATS in tackling emerging contaminants [40].

Constructed wetlands, one of the most widely adopted DEWATS components, achieve pollutant removal efficiencies of up to 90% for biochemical oxygen demand (BOD), alongside substantial nutrient and pathogen reductions [19, 26, 33, 35]. Floating treatment wetlands (FTWs) - an adaptation of conventional wetlands - have also shown strong performance with operational simplicity and low costs [13]. Anaerobic baffled reactors (ABRs) typically achieve BOD and chemical oxygen demand (COD) removal efficiencies of 60-75%, with the added benefit of potential biogas recovery [22, 26]. Hybrid configurations combining ABRs and constructed wetlands have been piloted in India, Turkey, and Latin America, confirming their technical viability and scalability potential [8, 24, 25]. These international experiences demonstrate that decentralized models, when well designed, can perform comparably to centralized systems while being more cost-effective and resilient in rural, water-scarce settings. Figure 2 presents a comparative summary of BOD and COD removal performance across several decentralized treatment technologies, adapted from global DEWATS pilot studies.

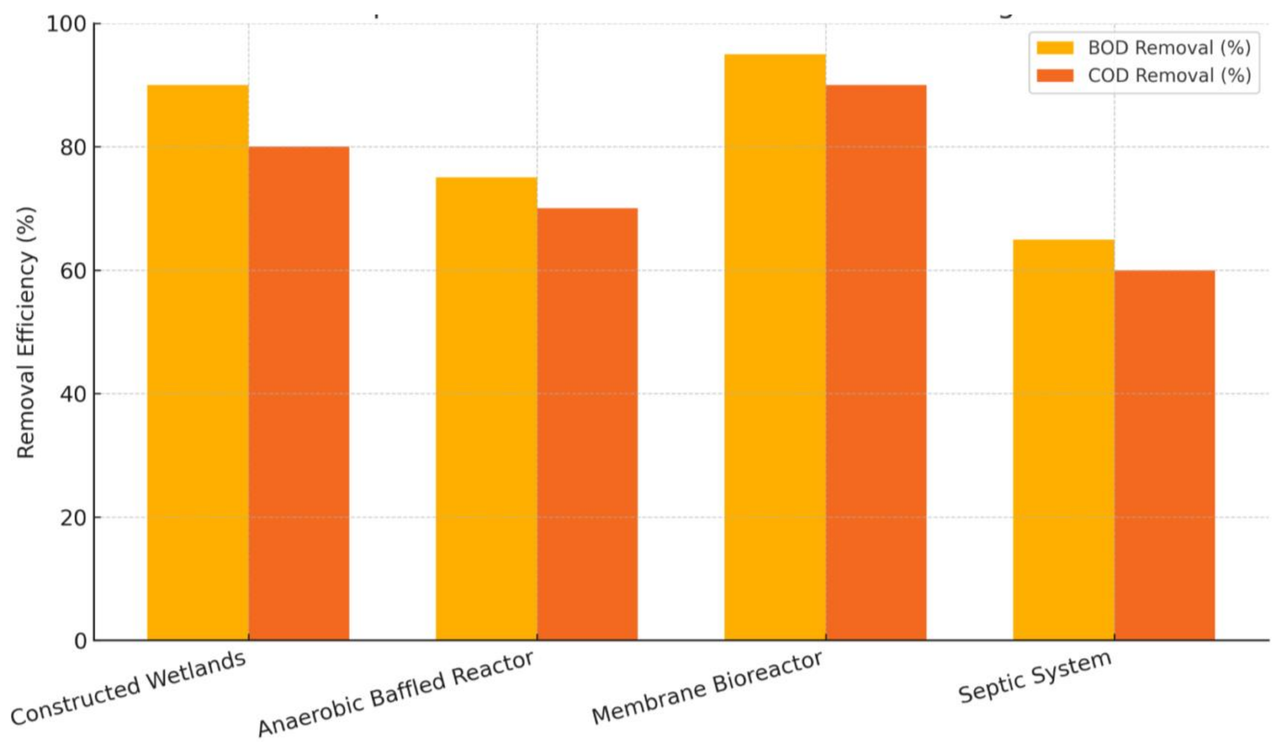

Figure 2. *Comparison of wastewater treatment technologies. BOD and COD removal efficiencies across decentralized treatment systems. Data adapted from global DEWATS pilot studies and literature sources.*

Beyond treatment efficiency, other critical selection factors such as maintenance and cost strongly influence adoption. Table 1 summarizes these aspects for four commonly applied decentralized wastewater treatment technologies: constructed wetlands, anaerobic baffled reactors, membrane bioreactors, and septic systems.

Table 1. *Performance comparison of selected decentralized wastewater treatment technologies. Data compiled from global pilot studies and literature sources. Prepared by authors.*

Technology	BOD Removal (%)	COD Removal (%)	Maintenance	Cost Level
Constructed Wetlands	90	80	Low	Low
Anaerobic Baffled Reactor	75	70	Moderate	Moderate

Membrane Bioreactor	95	90	High	High
Septic System	65	60	Low	Low

In Azerbaijan, preliminary pilot studies led by the Azerbaijan State Water Resources Agency (ADWRA) and the Ministry of Ecology and Natural Resources suggest that decentralized models can significantly improve sanitation in rural regions such as Shamakhi-Gobustan [4, 32]. The region's semi-arid climate, shallow groundwater, and inadequate infrastructure provide an ideal testbed for decentralized solutions [29, 31]. Seasonal rainfall variability, low stream flows, and aquifer vulnerability due to unregulated wastewater discharge further underscore this urgency [12, 36].

Bioremediation approaches have also gained attention as complementary strategies. Recent studies show that fungal species such as *Ganoderma* can degrade pharmaceutical residues and endocrine-disrupting compounds in wastewater, offering a low-cost and sustainable pathway [39]. Crop uptake studies confirm that untreated or poorly treated effluent may lead to pharmaceutical accumulation in agricultural products, raising food safety concerns [44]. These findings stress the importance of integrating biological remediation into decentralized treatment frameworks, particularly in semi-arid regions where eco-friendly and affordable solutions are needed.

To illustrate the comparative performance of different approaches, Table 2 synthesizes DEWATS configurations, highlighting pollutant removal efficiencies, operational requirements, and key trade-offs.

Table 2. *Comparative assessment of decentralized wastewater treatment system (DEWATS) configurations. Data synthesized from global pilot studies and literature sources [8, 19, 24-26, 33, 35]. Prepared by authors.*

Configuration	**BOD Removal (%)**	**COD Removal (%)**	**Energy Demand**	**Land Requirement**	**Cost Level**	**Key Advantages**	**Limitations**

ABR + Constructed Wetland	75-85	65-75	Low	Moderate	Low	Simple operation; biogas recovery	Sensitive to hydraulic fluctuations
Membrane Bioreactor (MBR)	90-95	85-90	High	Low	High	High effluent quality; compact	Expensive; maintenance-intensive
Septic Tank + Sand Filter	60-70	50-0	Very Low	Moderate-High	Very Low	Extremely low cost	Limited efficiency; pathogen risk
Constructed Wetland (CW)	85-90	75-80	Low	High	Low	Nature-based; robust in rural	Requires large land area

While international experience confirms DEWATS viability, little attention has been given to integrated modeling that validates performance in semi-arid and data-scarce conditions. Much recent literature focuses on pharmaceuticals and emerging contaminants [39, 40], but few studies combine field validation with performance modeling for decentralized systems in rural contexts. In parallel, digital technologies are reshaping wastewater recycling. IoT-enabled sensor networks integrated with hybrid recurrent neural networks (HG-RNN) have been applied to restore polluted ponds and enable real-time water quality monitoring [42]. Fuzzy-embedded RNNIoT frameworks have also been tested in sustainable coffee farming, showing how smart wastewater recycling can enhance environmental quality and resource use efficiency [43].

This literature review highlights the need to pilot and evaluate decentralized models tailored to Azerbaijan's rural conditions, drawing on international lessons. The findings reinforce the global imperative to achieve Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation) and SDG 11 (Sustainable Cities and Communities) [2, 21].

3. Methodology

3.1 Study Area and Site Selection

The Shamakhi-Gobustan region in central Azerbaijan was selected as the pilot area due to its semi-arid climate, shallow groundwater, absence of centralized wastewater infrastructure, and increasing vulnerability to environmental degradation. This region represents one of the most water-scarce parts of Azerbaijan, where rural communities are particularly exposed to the risks of untreated wastewater discharge.

Three rural settlements - Tekle and Jangi villages (Gobustan District) and Chukhuryurd village (Shamakhi District) - were chosen as representative study sites. Selection criteria included settlement size (500-2,000 inhabitants), proximity to surface water bodies (≤1 km), prevailing wastewater management practices (use of septic pits or uncontrolled discharge), and documented groundwater and aquifer contamination risks. The geographic coordinates of the pilot sites are Tekle, Jangi, and Chukhuryurd. Figure 3 illustrates the location of the study area and pilot villages relative to major hydrogeological features.

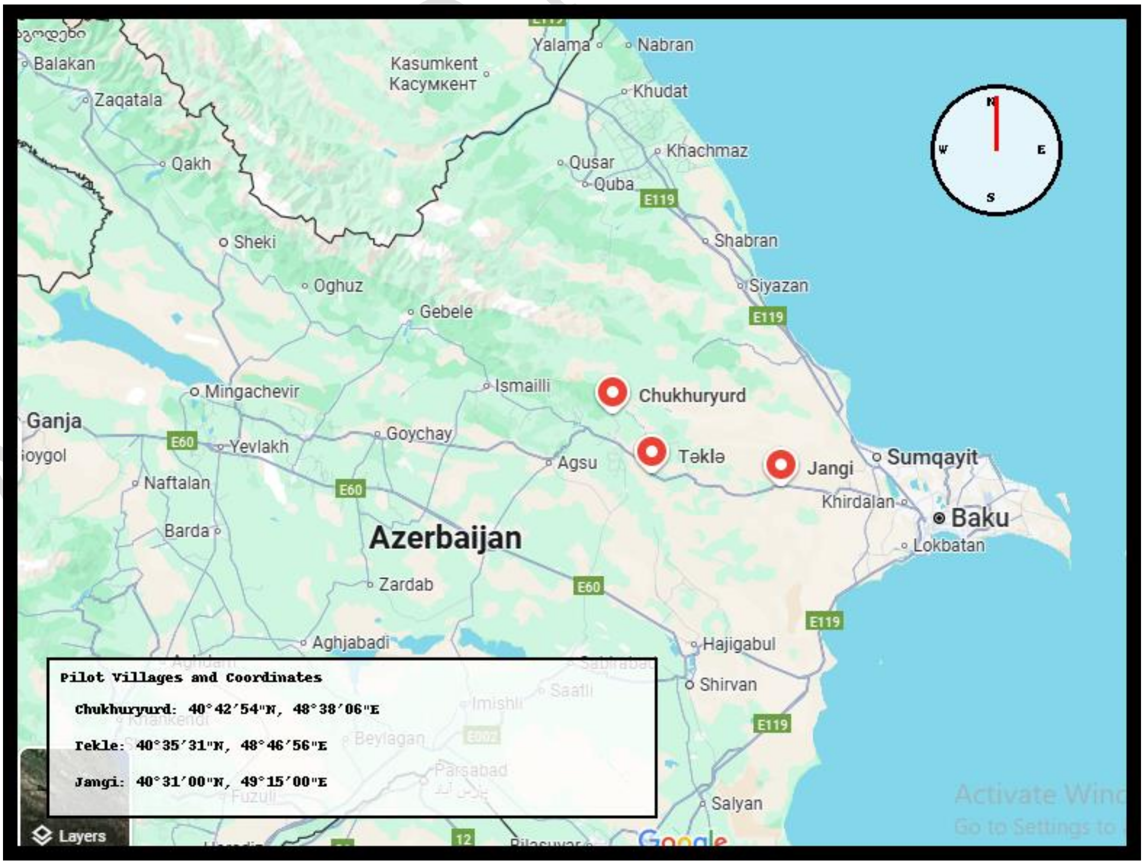

Figure 3. *Location map of the Shamakhi-Gobustan pilot villages (Tekle, Jangi, Chukhuryurd) within Azerbaijan, based on UN Geospatial data. Coordinates: Tekle 40°35'31" N, 48°46'56" E; Jangi 40°31'00" N, 49°15'00" E; Chukhuryurd 40°42'54" N, 48°38'06" E. Prepared by authors.*

Field access and technical implementation were supported through collaboration with "Aqualink" LLC, a private operator active in wastewater treatment projects across the Shamakhi-Gobustan region. The involvement of Aqualink facilitated system design, field sampling logistics, and community engagement, ensuring the pilot's feasibility under real rural conditions.

3.2 Field Sampling and Monitoring

Comprehensive sampling campaigns were conducted at five monitoring points in each village to assess the quality of surface water, groundwater, and untreated domestic wastewater. Seasonal sampling was carried out over a 12-month period, covering both dry and wet climatic conditions, with samples collected monthly. To ensure statistical robustness, three replicates were taken per monitoring point for each parameter.

Key pollution indicators included biochemical oxygen demand (BOD, mg/L), chemical oxygen demand (COD, mg/L), nitrate (NO_3^-, mg/L), total coliform bacteria (MPN/100 mL), and *Escherichia coli* (CFU/100 mL), measured in accordance with APHA Standard Methods [7].

All laboratory analyses combined field probes with bench-scale instruments. BOD and COD were quantified using Hach HQ40d portable meters with DR3900 spectrophotometric analysis, while nitrate concentrations were determined via the ion-selective electrode method (Thermo Scientific Orion). Microbial indicators (total coliforms and *E. coli*) were analyzed using membrane filtration and chromogenic substrate techniques.

Data processing and statistical evaluation were performed on a Dell Precision workstation (Intel Xeon 3.2 GHz, 32 GB RAM) using MATLAB R2024a and Python 3.11 (NumPy, SciPy, pandas, and matplotlib libraries). Network configurations enabled secure data logging and synchronization between field devices and the central database, ensuring reproducibility and data integrity.

3.3 System Design and Treatment Process

A pilot hybrid decentralized wastewater treatment system was constructed in Tekle village to evaluate performance under real rural conditions. The treatment configuration integrated four sequential components. First, a primary sedimentation tank was installed to remove suspended solids and reduce the initial pollutant load [6]. This was followed by an anaerobic baffled reactor (ABR), which reduced organic matter and initiated anaerobic digestion processes [16]. The effluent then passed into a horizontal subsurface flow constructed wetland planted with native macrophytes, enhancing nutrient uptake and pathogen removal through bio-physicochemical processes [11]. Finally, a solar-powered pumping and monitoring unit was employed to optimize hydraulic loading and ensure energy-efficient operation [17].

The system was designed for modularity, enabling replication and scaling in other rural communities. It combined low maintenance requirements with high treatment efficiency. Technical oversight and operational support were provided by the Azerbaijan State Water Resources Agency (ADWRA) and the Ministry of Ecology and Natural Resources, in collaboration with local partners. Figure 4 presents a schematic of the treatment train and flow direction.

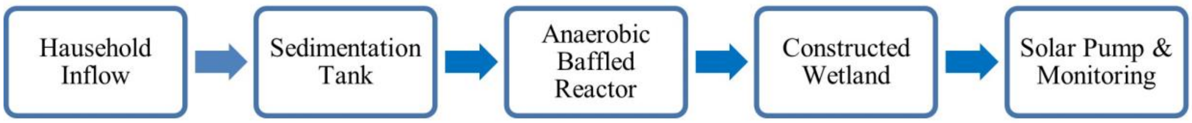

Figure 4. *Schematic of the hybrid decentralized wastewater treatment system implemented in Tekle village, Azerbaijan. The system integrates household wastewater inflow, sedimentation tank, anaerobic baffled reactor (ABR), horizontal subsurface flow constructed wetlands, and a solar-powered pumping and monitoring unit. Prepared by authors.*

3.4 Modeling Approach

To strengthen the analytical rigor, a mass balance-based performance model was developed to simulate pollutant removal efficiencies across each treatment stage [10]. The model assumed steady-state hydraulic conditions and consistent biological activity, reflecting operational parameters commonly observed in decentralized systems [9].

The pollutant removal efficiency RRR for each parameter was calculated as:

$$R = \frac{C_{in} - C_{out}}{C_{in}} \times 100$$

Where:

R = removal efficiency (%);

C_{in} = influent concentration (mg/L);

C_{out} = effluent concentration (mg/L).

Model inputs were derived from 12 months of field monitoring data, incorporating both wet and dry seasonal variations. The simulation focused on biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrate, and total coliform bacteria, representing the main pollution indicators in rural domestic wastewater.

To formalize the analytical workflow, the model development was translated into structured pseudo-code (Algorithm 1), which summarizes the logical sequence from data input to calibration and scenario evaluation.

Algorithm 1. Mass Balance-Based Modeling Framework

Input: Field monitoring data (Cin, Cout) for BOD, COD, Nitrate, Coliform

Step 1: Import data into MATLAB/Python environment

Step 2: Pre-process data (outlier removal, seasonal averaging)

Step 3: For each pollutant parameter:

    Compute R = (Cin - Cout)/Cin * 100

Step 4: Validate results by comparing simulated outputs with observed effluent data

Step 5: Perform scenario analysis:

    a) Adjust influent load (low, medium, high)

    b) Adjust hydraulic loading rates

c) Recompute removal efficiencies

Step 6: Output model results (R-values, error metrics, visualization)

End

Model outputs were validated against observed effluent concentrations. Performance evaluation used statistical indicators such as the coefficient of determination (R^2) and root mean square error (RMSE), confirming strong agreement between modeled and observed values. This framework enables scenario-based analysis and supports the evaluation of system scalability under varying environmental and design conditions [20, 21].

Figure 5 illustrates the overall methodological framework applied in this study, summarizing the sequential steps from field sampling to scenario analysis.

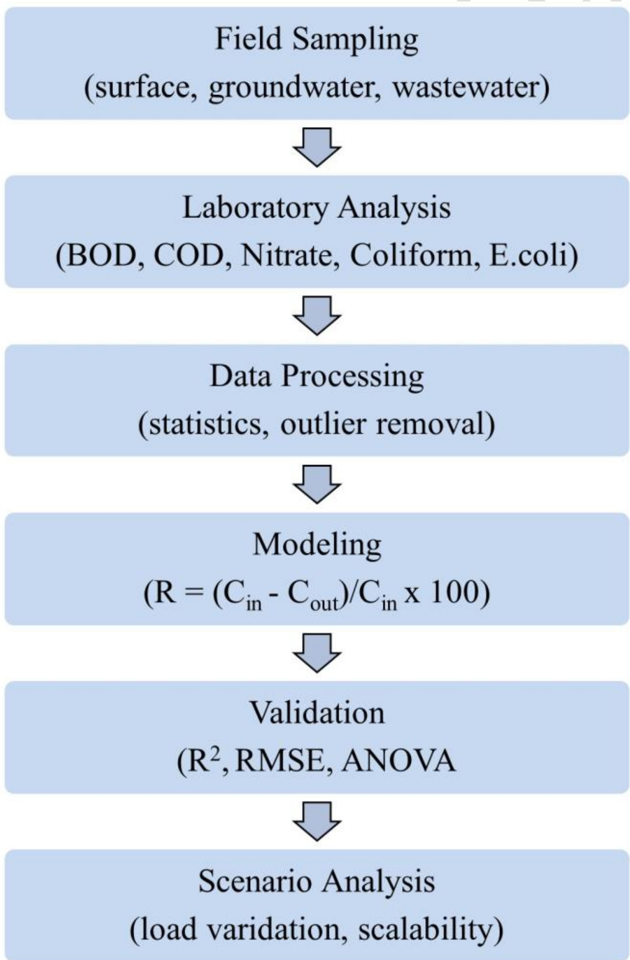

Figure 5. *Methodological flow diagram of the study, illustrating sequential steps from field sampling through laboratory analysis, data processing, modeling, validation, and scenario analysis. Prepared by authors.*

3.5 Model Results

The pollutant removal efficiencies obtained from the mass balance model, based on field-monitored influent and effluent concentrations, are summarized in Table 3. The results represent 12-month averages, accounting for seasonal variations in hydraulic load and pollutant levels. For microbial indicators (coliforms), results are reported as threshold values due to methodological limitations of enumeration.

Table 3. *Model-based removal efficiencies of the pilot decentralized wastewater treatment system (12-month averages, n = 3, mean ± SD). Prepared by authors.*

Pollutant	**Influent Concentration** C_{in} (mg/L)	**Effluent Concentration** C_{out} (mg/L)	**Removal Efficiency** (%)
Biochemical Oxygen Demand (BOD)	22 ± 3.1	3.3 ± 0.5	85 ± 4.2
Chemical Oxygen Demand (COD)	58 ± 6.7	18 ± 2.4	70 ± 5.1
Nitrate (NO_3^-)	65 ± 5.4	32.5 ± 3.8	50 ± 6.3
Total Coliform Bacteria (MPN/100 mL)	>100,000	<5,000	>95%

The model outcomes closely aligned with observed field data. Statistical validation confirmed a high level of agreement, with R2=0.94R^2 = 0.94R2=0.94 and RMSE = 4.2 mg/L for COD. Integration of field-monitored data into the simulations, combined with seasonal averaging, improved accuracy and captured climatic variability. No significant seasonal differences were detected (ANOVA, $p > 0.05$), demonstrating the system's stability and operational reliability under rural conditions.

Validation was conducted by systematically comparing modeled outputs with observed data collected throughout the 12-month campaign, confirming the robustness and reproducibility of the modeling framework.

These strong agreements validate the applicability of mass balance modeling for decentralized wastewater treatment systems in resource-limited settings [21, 22]. Moreover, the framework provides a versatile platform for scenario-based analysis, enabling adjustments to system scale, hydraulic loading, and influent pollutant concentrations. This flexibility supports design optimization, long-term performance forecasting, and comparative evaluation with alternative treatment configurations.

3.6 Limitations and Uncertainty Considerations

While the performance modeling in this study provides valuable insights into system efficiency and scalability, several limitations and sources of uncertainty should be acknowledged.

First, the monitoring duration was limited to a 12-month field campaign. Although this period captured both dry and wet seasonal conditions, it may not fully reflect interannual variability or extreme weather events that could affect treatment performance under long-term climatic fluctuations.

Second, the model relied on steady-state assumptions of hydraulic loading and biological activity. In practice, daily and seasonal fluctuations in flow rates and influent pollutant concentrations can lead to deviations from predicted values. Pollutant removal coefficients were also simplified, derived from averaged field data and literature benchmarks. These may not fully capture localized biological and geochemical processes, particularly under temperature extremes or operational disruptions.

Third, the pilot system was implemented in a single village (Tekle), limiting replication and generalizability. Although the results are encouraging, further validation across diverse rural contexts - varying settlement sizes, hydrogeological conditions, and socio-economic settings - is needed to confirm wider applicability.

Fourth, the absence of real-time monitoring technologies posed another limitation. Automated sensors and online data acquisition could have improved performance evaluation accuracy, facilitated early detection of anomalies, and supported proactive maintenance strategies.

Despite these constraints, the close alignment between modeled and observed results demonstrates that mass balance modeling is a practical and reliable tool for evaluating decentralized wastewater treatment in rural settings. Importantly, the identified limitations also provide direction for future research. Incorporating dynamic (time-variable) modeling approaches, sensitivity analyses, and real-time monitoring systems would enhance predictive accuracy, optimize operational strategies, and strengthen resilience planning. Linking these improvements to scenario analysis underscores that the model is not only valid under current conditions but also adaptable to stress scenarios, making it relevant for long-term rural sanitation planning under climate and institutional risks.

4. Results

Baseline field investigations confirmed that untreated domestic wastewater from households in Tekle, Jangi, and Chukhuryurd villages significantly contributed to surface and shallow groundwater contamination. Measured biochemical oxygen demand (BOD) ranged from 18-25 mg/L, while chemical oxygen demand (COD) reached 45-70 mg/L. *Escherichia coli* and total coliform counts exceeded WHO safety thresholds by factors of 50-100, and nitrate concentrations reached up to 65 mg/L, surpassing drinking water limits [3, 7, 29]. These findings highlight the urgent environmental and public health risks associated with unregulated wastewater discharge in the Shamakhi-Gobustan region.

The pilot decentralized wastewater treatment system in Tekle village achieved substantial pollutant reductions. Over 12 months of monitoring, the system removed on average 85% of BOD, 70% of COD, and 50% of nitrate. Coliform and *E. coli* levels were reduced by more than 95%, bringing effluent into compliance with WHO discharge standards [8, 24]. These results confirm that the system can effectively mitigate microbial and nutrient pollution in rural wastewater under semi-arid conditions. The corresponding average removal efficiencies with variability are summarized in Table 3 and visualized in Figure 6. Detailed monthly influent/effluent concentrations and removal efficiencies are provided in Supplementary Table S1.

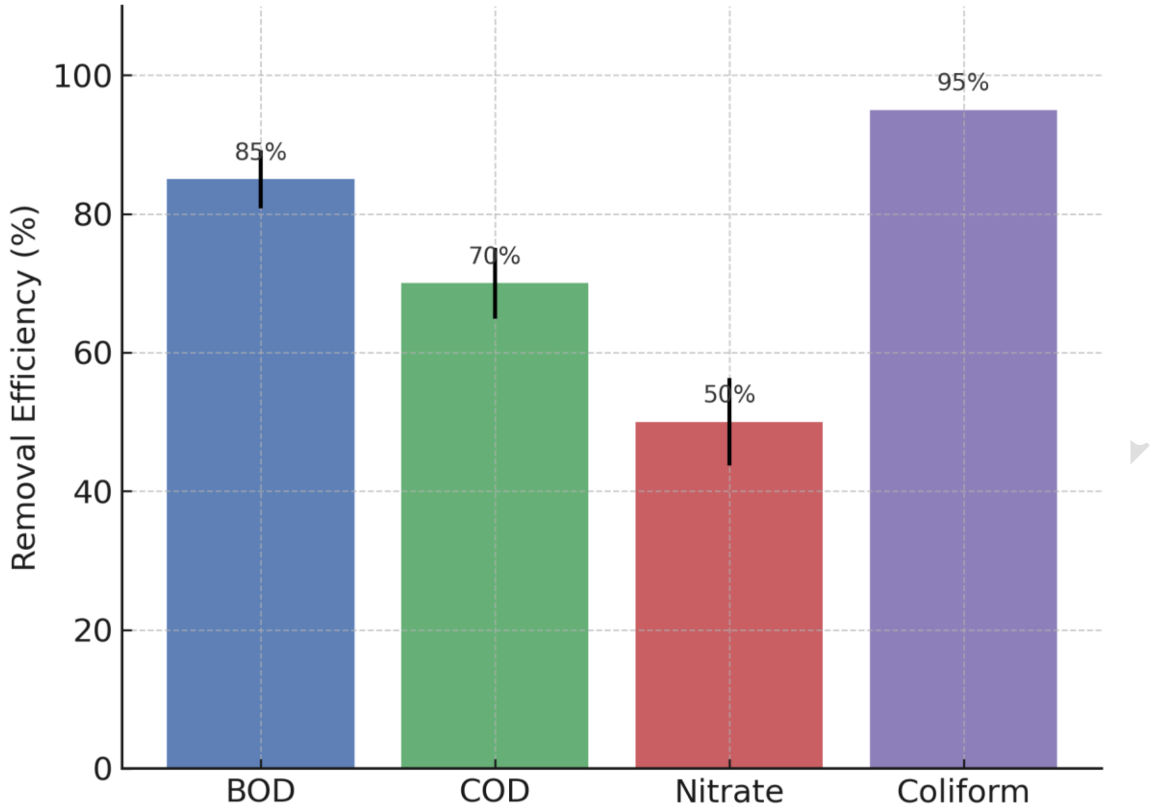

Figure 6. *Average pollutant removal efficiencies (BOD, COD, nitrate, coliform) achieved by the Tekle pilot DEWATS over a 12-month monitoring period (n = 3, mean ± SD). Error bars indicate standard deviation. Coliform removal is shown as threshold values due to methodological limitations. Prepared by authors.*

Model-based results closely aligned with empirical monitoring data, confirming the reliability of the mass balance framework. Simulated efficiencies indicated 85% BOD removal, 70% COD removal, 50% nitrate reduction, and over 95% pathogen elimination [9, 10, 24]. Statistical validation showed strong agreement between observed and modeled values (R2=0.94R^2 = 0.94R2=0.94, RMSE = 4.2 mg/L for COD), with no significant seasonal variation detected (ANOVA, $p > 0.05$). Validation was conducted specifically for the Tekle pilot, comparing observed influent/effluent data with modeled outputs. A scatter plot of observed versus modeled efficiencies is presented in Figure 7.

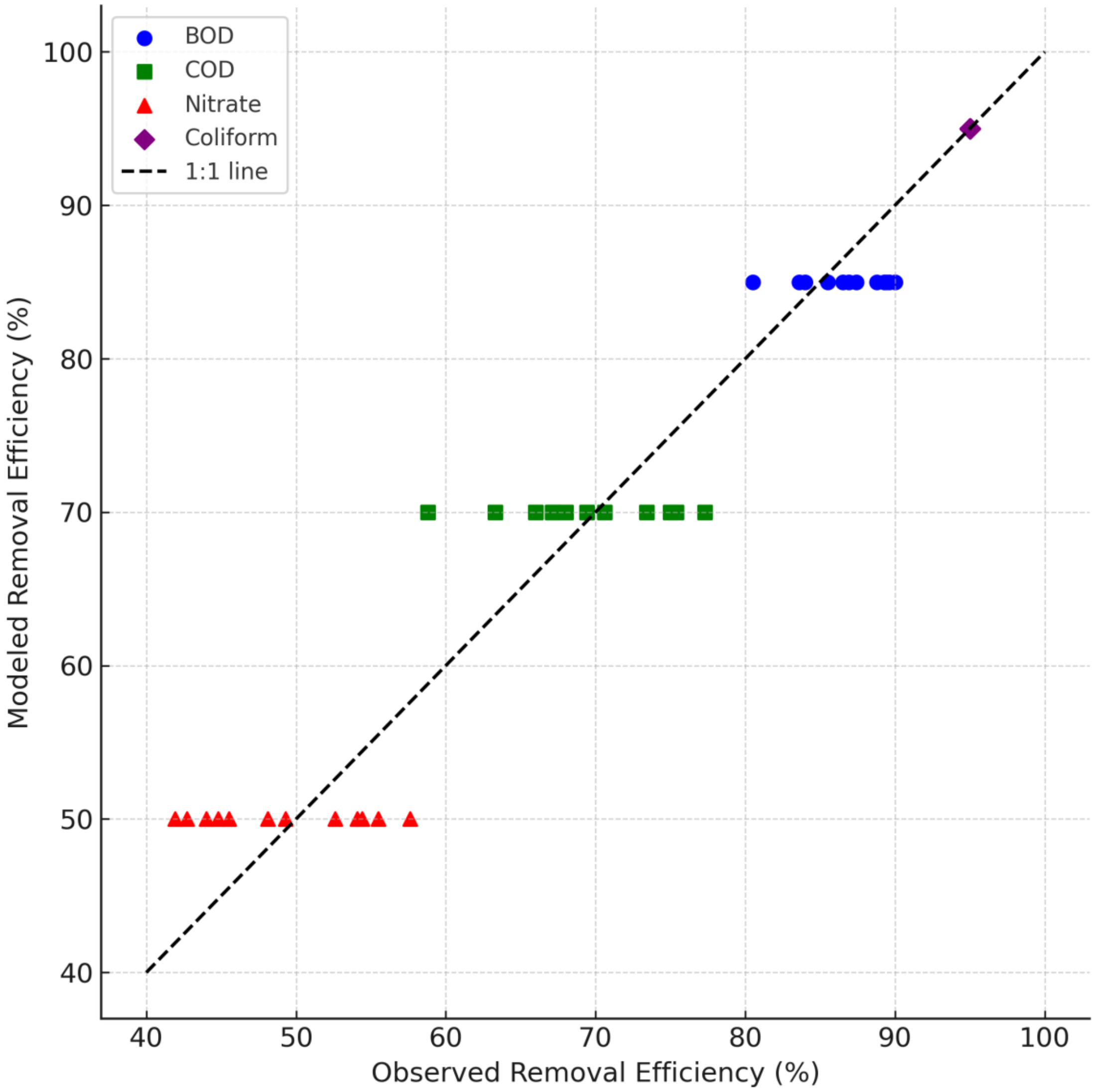

Figure 7. *Observed versus modeled pollutant removal efficiencies (BOD, COD, nitrate, coliform) for the Tekle pilot decentralized wastewater treatment system over a 12-month monitoring period. Each point represents monthly averages (n = 3), with modeled outputs based on the mass balance framework. The 1:1 dashed line indicates perfect agreement. Coliform results are plotted as threshold-based points (>95% removal). Prepared by authors.*

Although overall performance was high, nitrate removal remained comparatively lower (~50%). This reflects limited denitrification in the ABR and constructed wetlands due to short hydraulic retention times and low organic carbon availability. Similar challenges have been reported in other semi-arid DEWATS applications, where nitrate proved more resistant than organic pollutants [cf. 24].

A comparative analysis between Tekle effluent and untreated wastewater samples from Jangi and Chukhuryurd underscored the advantages of the hybrid system. Pollutant loads were consistently lower in treated effluent, particularly for BOD, COD, and microbial indicators. No significant seasonal variation in treatment performance was observed, confirming operational stability under semi-arid climatic conditions [4, 31]. Figure 8 illustrates the comparison between treated and untreated wastewater.

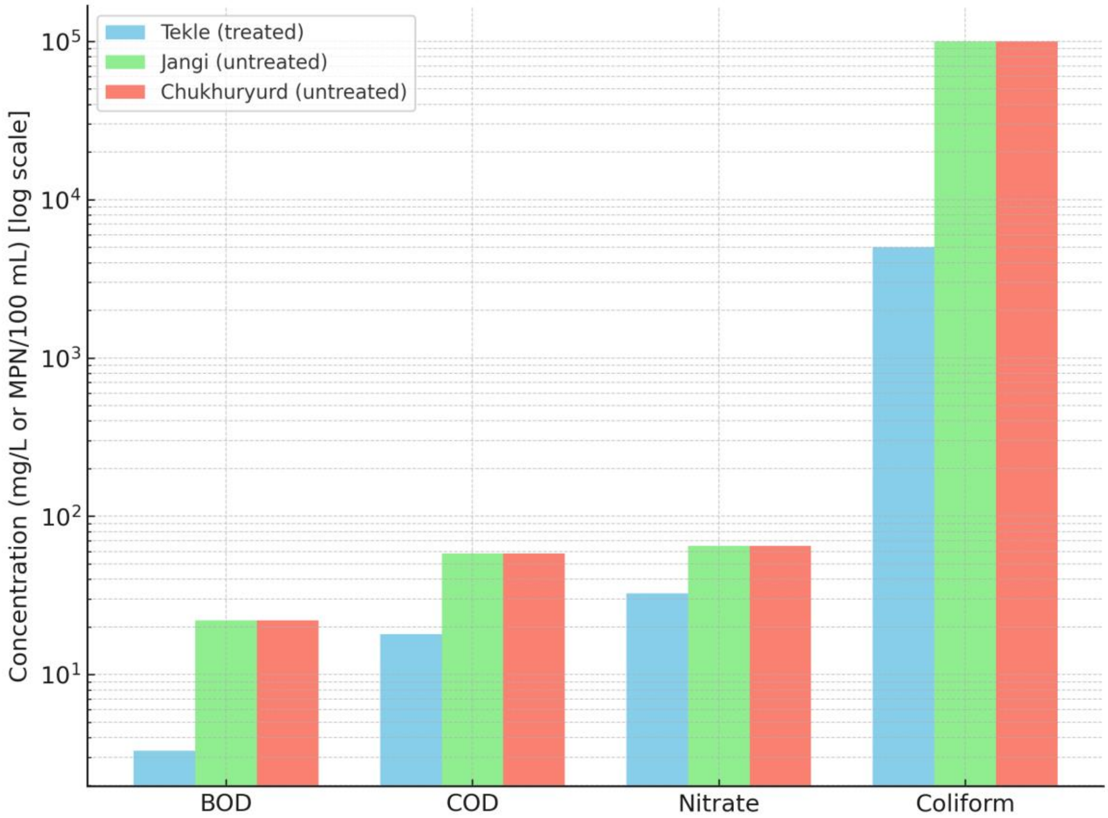

Figure 8. *Comparison of key water quality parameters (BOD, COD, nitrate, coliform) between treated wastewater from Tekle village and untreated domestic wastewater from Jangi and Chukhuryurd villages in the Shamakhi-Gobustan region. Data are shown on a logarithmic scale to account for large differences in coliform concentrations. Prepared by authors.*

These findings suggest that the hybrid DEWATS not only meets discharge standards but also provides long-term operational stability. Effluent BOD (~3.3 mg/L) and COD (~18 mg/L) levels fall well below international thresholds, while >95% pathogen reduction directly reduces sanitary risks for rural communities. The absence of seasonal variability confirms resilience under semi-arid climatic conditions, highlighting scalability to similar villages. Such stability and compliance underline the system's suitability as a cost-effective alternative to centralized treatment in resource-limited settings.

5. Discussion

The results of this study demonstrate that decentralized wastewater treatment systems (DEWATS) provide a viable and sustainable solution for rural and semi-urban areas, particularly in water-scarce regions such as Shamakhi-Gobustan. The Tekle pilot achieved substantial reductions in key pollution parameters - 85% for BOD, 70% for COD, 50% for nitrate, and over 95% for coliform bacteria. These outcomes are comparable to, and in some cases exceed, results from similar initiatives in Turkey, India, and Latin America, where constructed wetlands and anaerobic baffled reactors typically achieved BOD reductions of 75-80% [14, 17, 37]. The consistency of results underlines the adaptability of DEWATS to diverse climatic and socio-economic contexts.

The integration of a mass balance-based performance model quantitatively verified treatment efficiency, demonstrating strong alignment between simulated and observed results. This approach validated system stability under local conditions and enabled scenario-based analysis, supporting optimization under variable influent loads and hydraulic regimes [9, 10]. The Tekle case illustrates how performance modeling strengthens the scalability and transferability of decentralized sanitation technologies.

The hybrid configuration - combining sedimentation tanks, anaerobic baffled reactors, and constructed wetlands - proved both effective and energy-efficient. Solar-powered pumping minimized the carbon footprint and increased applicability in regions with limited or unreliable electricity. The modular design allows replication in other villages such as Jangi and Chukhuryurd with minimal adjustments. System security and operational reliability were reinforced by modularity and solar monitoring, reducing dependence on centralized grids. This versatility underscores the relevance of DEWATS as a climate-resilient and cost-effective strategy suitable for communities ranging from several hundred to several thousand inhabitants [13, 18, 34].

Barriers, Enablers, and Comparative Methods

Despite these advantages, contextual factors influence implementation. Barriers include upfront investment requirements, limited technical expertise for maintenance, and initial community reluctance due to unfamiliarity with decentralized sanitation. Enablers include low operational costs, renewable energy reliance, and improved community acceptance once water quality benefits became evident. In Azerbaijan, where rural wastewater infrastructure is largely absent, the Tekle pilot represents the first hybrid DEWATS field validation, serving as both a technical demonstration and a policy-relevant case.

In pollutant removal efficiency, the Tekle pilot outperformed many stand-alone physical and chemical methods. Coagulation-flocculation typically achieves 50-60% BOD reduction, while chemical oxidation may reach ~65% COD removal but with higher costs and energy demands. Biological systems such as activated sludge can deliver 85-90% BOD reduction but are maintenance-intensive and less suited to rural contexts. By contrast, the Tekle hybrid DEWATS combined comparable efficiency with lower energy use and simpler operation, aligning with findings on integrated natural treatment systems [cf. 18]. While membrane-based processes (NF/RO) can exceed 90% COD removal and address emerging contaminants, their high energy intensity restricts rural deployment [15, 40]. Constructed wetlands and ABRs consistently achieve 70-85% reductions with minimal operational demands [14, 17, 19, 22]. The Tekle pilot achieved results at the higher end of this range, confirming that hybrid integration can approach advanced treatment performance while remaining feasible in semi-arid, resource-limited conditions.

Recent studies broaden this perspective. Bioremediation approaches, such as fungal-based degradation, have demonstrated effective removal of pharmaceuticals and organic contaminants [39, 44]. Advances in smart monitoring - including IoT-enabled sensor networks and hybrid recurrent neural networks (HG-RNN) - show potential for real-time optimization of decentralized systems [42, 43]. Integrating such innovations with modular DEWATS could enhance resilience, enable adaptive operation, and extend applicability to a wider range of pollutants.

These findings support global sustainability agendas, particularly SDG 6 (Clean Water and Sanitation) and SDG 11 (Sustainable Cities and Communities). Given increasing climate variability and water scarcity, decentralized systems provide resilience advantages over centralized networks, which often face high operating costs, complex maintenance, and vulnerability to power disruptions. Despite promising outcomes, limitations remain. The monitoring period was limited to 12 months; extended multi-seasonal assessments are required to confirm long-term reliability. Additional pilots across varied semi-arid and data-scarce contexts would improve generalizability. Future research should also explore integration of smart sensors, real-time monitoring, and advanced modules, paving the way for next-generation decentralized sanitation frameworks adapted to rural and peri-urban conditions [10, 18, 20].

6. Conclusion

This study demonstrates that decentralized wastewater treatment systems (DEWATS) are an effective, low-cost, and climate-resilient sanitation option for rural and semi-urban communities. The Tekle pilot achieved high pollutant removal (BOD 85%, COD 70%, nitrate 50%, coliforms >95%), with effluent meeting WHO discharge standards. Integration of a mass balance-based performance model validated these outcomes and provided a scalable framework for optimization and replication in other water-scarce and infrastructure-limited regions.

The study highlights three key take-home messages:

1. **Technical and environmental performance:** Hybrid DEWATS integrating sedimentation tanks, anaerobic baffled reactors, constructed wetlands, and solar-powered components deliver reliable pollutant reduction with minimal energy demand and maintenance.
2. **Transferability and modularity:** The adaptable design supports replication in diverse socio-environmental contexts, both within and beyond Azerbaijan.
3. **Policy and sustainability relevance:** By bridging rural sanitation gaps, this approach directly contributes to SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action), while reinforcing national and local strategies for climate-resilient infrastructure planning.

While limitations remain - notably the 12-month monitoring period and implementation in a single pilot site - future research should expand multi-seasonal evaluations, test applicability across varied rural contexts, and integrate smart sensors, real-time monitoring, and scenario-based modeling. These improvements will enhance predictive accuracy, operational efficiency, and inform the development of next-generation smart decentralized sanitation frameworks.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Field data were collected in collaboration with Aqualink LLC and local authorities in the Shamakhi-Gobustan region of Azerbaijan.

Conflict of Interest Statement

The authors declare that they have no known financial or personal competing interests that could have influenced the work reported in this paper.