

Research Article

Translational Assessment of a Decentralized Sewage Treatment Plant for Sustainable Water Reuse and Circular Bioeconomy Applications

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Abstract

Rapid urbanization, industrialization and increasing freshwater deficiency require decentralized wastewater treatment solutions that establish both regulatory compliance and real-world applicability. The present study demonstrates the translational performance assessment of a decentralized sewage treatment plant (STP) specially made in 2015 at JK Township, Rayagada, India, with a capacity of 3000 m³/day with the operational load of approximately 1700 m³/day. The STP treats domestic sewage generated from residential colonies, canteens, and administrative facilities using an integrated treatment system which includes biological processes, flocculation, sedimentation, filtration, and disinfection. Performance evaluation was performed by using analytical data, which includes physio-chemical and biological parameters such as pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS), and fecal coliform. The results reveal high removal efficiencies of 91.3% for BOD, 93.1% for TSS, and 97.1% for fecal coliform, with treated effluent consistently meeting Consent to Operate (CTO) discharge standards. In addition to the conventional compliance review, this research also suggests the translation routes to the treated wastewater reuse to non-drinkable uses like cooling tower make-up, landscape garden, and plantation activities, which would support a zero liquid discharge strategy. Additionally, Sludge management and internal water recirculation enhance operational sustainability. The result further confirms that decentralized STPs can serve as dependable, scalable, and circular bioeconomy-aligned solutions for sustainable wastewater management in urban and semi-urban regions.

Keywords

Decentralized Sewage Treatment, Performance Evaluation, Sustainable Water Reuse, Circular Bioeconomy, Zero Liquid Discharge

1. Introduction

Increasing urbanization, industrial expansion, and water scarcity have deepened the need for sustainable wastewater

management systems capable of ensuring regulatory compliance and environmental protection. Conventional centralized

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sewage treatment systems often require extensive infrastructure, high capital investment, and long conveyance networks, limiting their suitability for industrial townships and semi-urban regions [1, 2]. Decentralized sewage treatment plants (STPs) provide operational flexibility, reduced infrastructure requirements, and improved opportunities for localized water reuse. Wastewater has been recognized globally as an underutilized resource with significant reuse potential [9].

Recent reports have proved the efficiency of decentralized wastewater treatment systems in various conditions of operations. In their study, Singh et al. described uniform removal efficiencies and regulatory adherence in decentralized treatment systems that were used in Indian environments [3]. The same researcher Varma et al. compose a review of decentralized wastewater treatment technologies in India and highlighted their technical feasibility, cost-effectiveness, and ability to adjust to changing conditions in hydraulic loading [4]. The results support the increased significance of decentralized systems as the alternative to centralized infrastructure.

In addition to the elimination of pollutants, modern wastewater management is also exposed in terms of a circular bioeconomy. The process of recovering resources out of wastewater, such as reuse of water, recycling of nutrients, and valorization of sludge, is a part of sustainable development and a lighter environmental footprint [5]. Microbial and bio-based treatment methods also increase the possibilities of integrated recovery pathways in decentralized systems [5, 6]. Nonetheless, in spite of the rich literature on decentralized technologies, there are few field-scale experiments centered on the long-term stability of operation when partially hydraulic loaded and the reuse application in the field of industrial township settings is recorded.

M/s J K Paper Pvt. Ltd., Rayagada, commissioned a decentralized STP in 2015 with a design capacity of 3000 m³/day to treat domestic sewage generated from residential colonies, township areas, and administrative facilities. The current influent load averages approximately 1700 m³/day, providing a unique opportunity to assess plant performance under partial-load conditions and evaluate operational robustness.

Thus, the current research will assess the effectiveness of the decentralized STP in treating the key physio-chemical and biological indicators, determine the adherence to the Consent to Operate (CTO) standards of discharge, and discuss the opportunities of translational use of the treated wastewater in the reuse of the wastewater and sustainable sludge management in a cycle bioeconomy. In this regard, translational assessment is understood to be the combination of field-scale performance validation, regulatory compliance testing, and practical reuse test under actual industrial township conditions. This paper

fills a gap in empirical research on the literature of the field through a mixture of technical assessment and sustainability insights on semi-urban wastewater systems in Indian locations.

2. Materials and Methods

2.1. Sewage Collection and Hydraulic Capacity

The township and colony sewage that is produced by the domestic sewage is collected using a gravity-based sewer system into four collection pits that have a cumulative capacity of 250 m³. The sewage gathered is pumped through bar screens to eliminate coarse solids before being pumped to the STP in an oil and grease separation chamber. The plant has been planned with 3000 m³/day capacity, and the average influent is 1620 to 1700 m³/day meaning that there is sufficient hydraulic capacity at the current operating capacities.

2.2. Treatment Process Description

The decentralized STP is a series of physical/chemical, and biological treatment units, which are aimed to be used in the efficient removal of organic matter, suspended solids, and microbial contaminants. The influent is then passed through the preliminary screening and removal of oil and grease followed by an equalization tank, which maintains a constant flow and homogenization of wastewater properties. The wastewater is then subjected to an anoxic tank to allow the process of denitrification and the diffused aeration tank where the aerobic microorganisms destroy the organic pollutants under regulated conditions of dissolved oxygen. Chemical conditioning is done in a flocculation chamber where alum, lime and polyelectrolytes are introduced to strengthen coagulation and PH regulation. The flocculated wastewater is introduced into a tube settler, where it is possible to separate the solid and liquid phases. Cleared effluents are chlorinated with sodium hypochlorite in a chlorine contact tank in order to inactivate the pathogen. The treated effluent is then disinfected using duplicate media and activated carbon filters to eliminate the remaining turbidity, color, odor and chlorine. The treated water is stored in treated water tank and re-use in the plant to cool tower make-up, which contributes in supporting a strategy of zero liquid discharge (ZLD). Sludge produced at the settling units is thickened and dewatered with a centrifuge and used as manure to plantation activities and the filtrate is reused in the STP inlet. The overall configuration of the STP is illustrated in Figure 1.

Process Flow Diagram of the Decentralized Sewage Treatment Plant

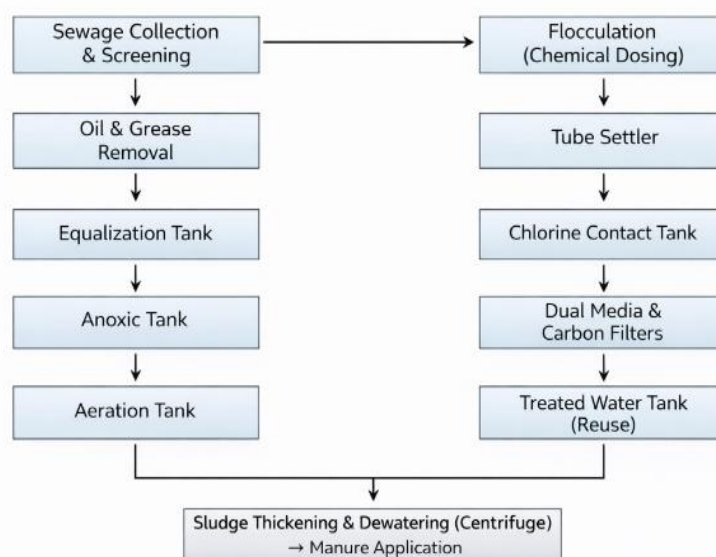


Figure 1. Process flow diagram of the decentralized sewage treatment plant showing major treatment units, sludge handling, and treated water reuse pathways.

2.3. Sampling and Analytical Methods

Wastewater samples were collected from the STP inlet and outlet point and analysed as per standard laboratory protocols. Important parameters including pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS), and fecal

coliform were analyzed following Standard Methods for the Examination of Water and Wastewater [7]. Analytical procedures were done would adhere to the protocols required by NABL to provide accuracy and reproducibility. Each analysis was done in three repetitions ($n = 3$) and the results are represented as mean $\pm$ standard deviation.

Table 1. STP Inlet and Outlet Water Quality Characteristics.

Parameter	Unit	Influent (Mean $\pm$ SD)	Effluent (Mean $\pm$ SD)	CTO Limit
BOD	mg/L	72 $\pm$ 2.1	6.2 $\pm$ 2.3	30
COD	mg/L	320 $\pm$ 4.0	60 $\pm$ 2.9	—
TSS	mg/L	112 $\pm$ 4.5	7.7 $\pm$ 3.3	100
TDS	mg/L	1752 $\pm$ 2.9	1351 $\pm$ 1.9	—
Fecal Coliform	MPN/100 mL	1800 $\pm$ 12	160 $\pm$ 6.2	1000

3. Results

The available decrease of BOD, COD and TSS performance is aligned with the performance trends of the decentralized wastewater treatment systems that have been used under similar hydraulic and organic loading conditions [4, 5]. The use of chlorination as a tertiary process of disinfection is confirmed using a high fecal coliform removal. The discharge

standards of CPCB were always satisfied by the treated effluent [8].

3.1. Treatment Performance

The BOD removal efficiency of 91.3% obtained shows that the microbial degradation is carried out effectively by aerobic microbes in the stable dissolved oxygen environment. The re-

removal of COD (81.0) indicates that there are non-biodegradable fractions remaining and that is normal in domestic wastewater that does not undergo advanced oxidation. The elevated TSS removal (93.1) verifies effective solid-liquid separation obtained by the combinations of coagulation, tube settling and filtration units. There is reduction of fecal coliform of 97.1% which is a testament of good disinfection performance. The measured removal efficiencies agree with known ranges of performance of decentralized wastewater treatment systems that are run under similar hydraulic loading conditions [4, 5]. Figure 2 and Figure 3 provide the comparative concentrations of influent and effluent and all the calculated removal efficiencies respectively.

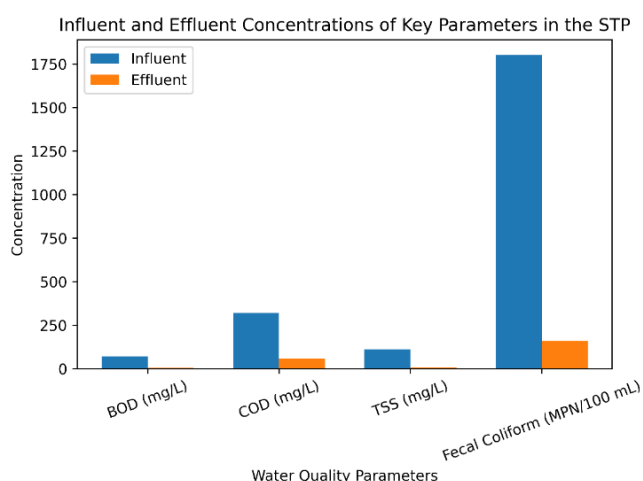


Figure 2. Influent and effluent concentrations of key water quality parameters in the decentralized sewage treatment plant.

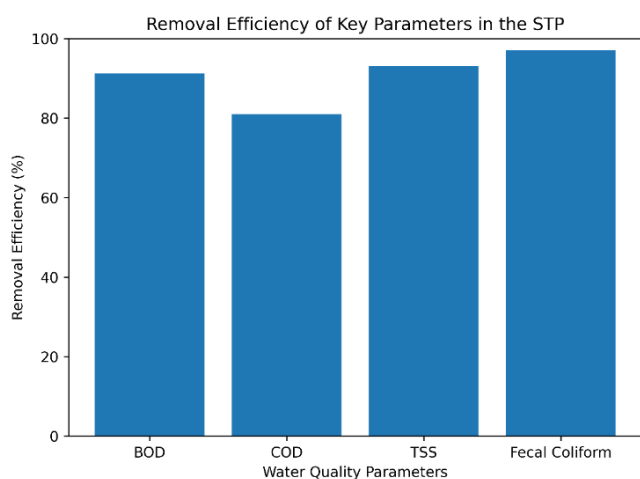


Figure 3. Removal efficiency of key water quality parameters in the decentralized sewage treatment plant.

3.2. Reduction Efficiency Analysis

The effectiveness of the decentralized sewage treatment plant in the reduction of essential water quality parameters

was compared between influent and effluent concentrations and the removal efficiencies were calculated and are summarized in Table 2. The STP had a high biochemical oxygen demand (BOD) removal efficiency of 91.3 that showed good organic matter degradation in the STP under controlled aeration conditions. The effectiveness of 81.0 percent in chemical oxygen demand (COD) removal indicates high levels of reduction of the biodegradable and non-biodegradable organic components as a result of combining the biological treatment with the physicochemical processes.

A suspended solids (TSS) removal efficiency of 93.1% indicates effective solid-liquid separation by use of coagulation, flocculation, settling and filtration units hence the appearance of clear treated effluent. Moreover, the fecal coliform reduction was 97.1% which is an indication of the efficiency of the disinfection system in reducing the microbial contamination significantly and in meeting the regulatory threshold in discharges. In general, the identified reduction efficiencies confirm the predictable and consistent behaviors of the STP in the real operating conditions and confirm its appropriateness to the use of non-potable water reuse.

Table 2. Reduction Efficiency Analysis.

Parameter	Reduction Efficiency (%)
BOD	91.3
COD	81.0
TSS	93.1
Fecal Coliform	97.1

4. Discussion

The findings establish the fact that the decentralized STP is efficient when used in the real field and is able to comply with regulatory discharge limits. The removal efficiencies in this research are high thus proving to be effective in nature of the integrated biological treatment, flocculation, filtration and disinfection process. It has also been observed that decentralized STPs to manage sustainable urban wastewater have reported similar performance levels [3, 4]. A partial hydraulic load operation has not had a negative impact on the treatment efficiency, which shows sufficient design margins and flexibility of operations. The efficiency of BOD removal in this research (91.3) is similar to the levels of efficiency reported in the decentralized treatment systems in India (85-95) [4, 5], which suggests that the process works uniformly with the low hydraulic loading.

A translational viewpoint of reuse of treated wastewater in cooling tower make-up and plantation activities will lower freshwater abstraction and enhance a zero liquid discharge (ZLD) scheme, highlighted in sustainable water reuse research

[10]. In addition, dewatering of sludge and land application lead to resource recovery and comply with the principles of the circular bioeconomy [6]. This system is shown to be scalable and replicated to other resembling industrial townships and semi-urban developments.

5. Conclusions

The decentralized STP was found to be stable and efficient in pollutant removal when partially loaded hydraulically, with high pollutant removal efficiencies of BOD, COD, TSS and fecal coliform and continually met regulatory requirements. Combining the reuse of treated wastewater and the valorization of sludge sustainably meet water management and the agenda of the circular bioeconomy. The results confirm that decentralized STPs have a translational expanse to industrial townships and semi-urban areas.

Abbreviations

STP	Sewage Treatment Plant
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
TSS	Total Suspended Solids
TDS	Total Dissolved Solids
CTO	Consent to Operate
ZLD	Zero Liquid Discharge

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Author Contributions

Ripu Kumar Sahu: Investigation, Data curation, Writing – original draft

Radha Krushna Padhi: Conceptualization, Supervision, Formal analysis, Writing – review & editing

Manoja Das: Methodology, Validation, Visualization

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Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



Ripu Kumar Sahu is a Ph.D. Scholar in the field of Engineering and Applied Sciences, actively engaged in academic research and interdisciplinary studies. His research interests include environmental pollution and its control, process engineering, emerging technologies, and sustainable scientific developments. He has contributed to research publications in reputed journals and conference proceedings.



Radha Krushna Padhi is presently serving as an Associate Professor in the field of Chemical Engineering at GIET University, with more than 21 years of teaching experience. He is an academician and researcher with expertise in process engineering, heat transfer, fluidization, and environmental engineering. He is actively involved in teaching, research, and academic administration. His research interests include process safety, sustainable energy systems, and multiphase flow studies. He has published several research papers in reputed national and international journals and conference proceedings.



Manoj Das is a prominent academic and researcher, currently leading the Department of Biotechnology at Gandhi Institute of Engineering and Technology University, Odisha, Gunupur. With extensive experience in biotech research, teaching, and administration, he has made significant contributions to nanobiotechnology, microbial biotechnology, natural products, and plant biotechnology. His research primarily focuses on green nanoparticle synthesis, probiotics, phytochemical analysis, and the development of bio-functional materials for healthcare and agriculture. Dr. Das has published extensively in reputable national and international journals and mentor students at all levels. He has led numerous projects funded by DBT, BIRAC, MSME, and AICTE.

Research Field

Ripu Kumar Sahu: Applied Sciences, Environmental Sciences

Radha Krushna Padhi: Chemical engineering

Manoj Das: Plant biotechnology, Botany