

Smart Monitoring of Small-Capacity Sewage Treatment Plants Using Internet of Things (IoT): A Real-Time and Predictive Approach

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ABSTRACT- Small capacity sewage treatment plants (STPs) are often poorly monitored, which results in uneven effluent quality, high operational costs, frequent equipment failures and non-compliance with regulatory norms. The present work deals with the implementation of Internet of Things (IoT) technology for smart real-time monitoring of STPs, notably for 0.5-5 MLD decentralized systems. IoT-enabled sensor networks were used for continuous monitoring of the essential parameters such as pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), flow rate and energy usage. Results demonstrate very high improvements by introduction of IoT. Real-time data transmission and automatic alerts helped reduce operational downtime by over 65%, increase effluent quality compliance by 82%, and reduce overall maintenance expenses by 45-55%. Predictive maintenance capabilities allowed for early detection of problems resulting in 30-40% energy savings and enhanced process stability. The proposed IoT framework is perfectly integrated with the existing hybrid treatment units and provides an easy-to-use dashboard for remote monitoring and data-driven decision making. The findings validate that IoT-based smart monitoring converts conventional STP activities into effective, sustainable and compliant systems. This strategy is in line with the national missions such as SBM-U 2.0 and NGT standards, provides a viable and scalable solution for small and medium towns, and encourages water reuse and environmental sustainability.

KEYWORDS: IoT in Wastewater Treatment, Smart STP Monitoring, Real-Time Sensor Network, Decentralized Sewage Treatment, Predictive Maintenance.

I. INTRODUCTION

Reliable operation of small capacity sewage treatment plants (STPs) of capacity 0.5 to 5 million litres per day (MLD) is based on effective monitoring. These decentralized facilities are an important infrastructure for wastewater management in small and medium towns, and help in meeting the stringent effluent discharge standards set by regulatory bodies such as the Central Pollution Control Board (CPCB) and National Green Tribunal

(NGT). Proper monitoring ensures consistent treatment performance, early detection of operational problems, optimum use of resources and protection of receiving water bodies. Strong monitoring in the context of India's Swachh Bharat Mission-Urban (SBM-U) 2.0 and AMRUT schemes directly supports public health, environmental sustainability and water reuse programs.

Small STPs are faced with many challenges with traditional manual monitoring systems that affect overall efficiency. Operators typically depend on periodic grab sampling and laboratory analysis – a time consuming, labour intensive and error prone process. This approach provides only discrete data points, not continuous insights, often resulting in a delayed response to process upsets such as shock loads, equipment malfunctions, or aeration failures. Other limitations involve a high dependence on skilled manpower (which is scarce in remote areas), inconsistent data recording, poor traceability, and difficulty to maintain regulatory compliance. As a result, many small STPs tend to be non-compliant, costly to operate and maintain, energy intensive and provide sub-optimal effluent quality.

The Internet of Things (IoT) technology has the transformative potential to modernize STP operations through real-time, automated and intelligent monitoring. In this way, IoT systems allow for constant monitoring of key parameters and the immediate communication of information to operators and decision makers through low-cost sensors, wireless communication modules, cloud platforms and data analytics. This change from reactive to proactive management enables remote supervision, automatic notifications, predictive maintenance and optimization of treatment processes based on data. The study deals with the practical application of IoT for the smart monitoring of small-capacity STPs (0.5–5 MLD), especially in hybrid treatment configurations. It highlights the benefits of embedding IoT to boost process stability, reduce operating costs, ensure compliance and achieve sustainable wastewater management in resource constrained environments. This IoT based approach is a major step towards smart, efficient and sustainable operation of distributed sewage treatment facilities.

II. LITERATURE REVIEW

The rapid development of the Internet of Things (IoT) has transformed traditional wastewater treatment systems into intelligent and networked infrastructures, which are capable of real-time monitoring and automated decision-making. The IoT provides an ongoing collection of operational data via distributed sensors, wireless communication, cloud computing and data analytics which increases treatment efficiency and lessens manual intervention [6], [7].

IoT based monitoring system for water quality assessment has been investigated by several researchers. Perumal et al. [8] proposed an IoT-enabled smart water monitoring framework to continuously monitor the critical parameters such as pH, turbidity, dissolved oxygen (DO) and temperature using low-cost sensors through cloud platforms. Their work showed that continuous monitoring gives a significant improvement in operational reliability over traditional approaches of sampling in the laboratory.

Wireless sensor networks (WSNs) have also benefited water quality monitoring as they provide the communication backbone for IoT-enabled environmental applications. Daigavane and Gaikwad [9] proposed wireless sensor network architecture for real time monitoring of multiple parameters of water quality. Their findings demonstrate that automated sensing can reduce human error and rapidly identify abnormal situations in water treatment plants.

Cloud computing is becoming more and more important for IoT-based wastewater management as it offers centralized storage, visualization and analysis of sensor data. Gubbi et al. [7] defined IoT as an integrated ecosystem of sensors, communication networks, cloud services, and intelligent analytics for smart infrastructure applications. Their framework provides the technological basis for the deployment of smart sewage treatment plants (STPs) that can handle large volumes of operational data in support of decision making.

In recent years, the integration of artificial intelligence and machine learning has been increasingly used in IoT-enabled wastewater treatment. Machine learning algorithms can use historical operational data to predict equipment failures, optimise aeration systems and detect anomalies before the plant's performance deteriorates. According to Lee et al. [10], predictive maintenance models have proven to be effective in reducing equipment downtime and maintenance costs by detecting abnormal operating conditions in advance. Such prediction is especially useful in decentralized STPs where skilled maintenance workers may not be readily available.

Energy consumption is still one of the major operational costs in the sewage treatment plants, mainly due to the fact that aeration systems account for almost half of the total electricity consumption. The use of IoT-based automation systems enables continuous monitoring of dissolved oxygen concentrations and dynamic adjustment of blower operation to meet treatment demand. Olsson reported that advanced aeration control strategies reduce energy use significantly, while maintaining the biological treatment efficiency [11]. Similar observations have been reported in modern smart wastewater treatment facilities with sensor-driven process optimization.

Several researchers also have explored the role of IoT in enhancing regulatory compliance and environmental sustainability. Continuous monitoring helps treatment operators to keep the effluent parameters within permissible discharge limits as it immediately alerts whenever any deviation occurs. The International Water Association (IWA) states that "Digital water technologies can greatly enhance the reliability of the process, the utilization of resources, and the opportunities for water reuse in modern wastewater treatment systems [12].

Ahsan et al. [13] presents the promising potential of DL based optimized models for effective network anomaly detection in IoT enabled cloud environment. They discuss the importance of DL approaches to address the key challenges, such as scalability, adaptability, and real-time threat detection. They have systematically reviewed the state-of-the-art models with their structures, optimization strategies and performance indicators. A comparison of the models is also undertaken to determine strengths, flaws and applicability of the models for different application scenarios.

However, there are some challenges in implementation despite these technological advancements. There are still issues of sensor fouling, communication failures, cybersecurity concerns, calibration needs, and limited internet connectivity, which need to be addressed for long-term deployment, particularly in rural and small-capacity treatment plants. Edge computing, low-power communication technologies (such as LoRaWAN), and hybrid cloud architectures have emerged as effective solutions to overcome these limitations, while maintaining reliable system performance [7], [14].

III. METHODOLOGY

A. The research framework

The study suggests an IoT based smart monitoring framework to improve the operational efficiency, reliability and sustainability of small capacity sewage treatment plants (STPs) having treatment capacities ranging from 0.5 MLD to 5 MLD. The proposed methodology combines the sensor networks, wireless communication, cloud computing, real time analytics and predictive maintenance in one monitoring system. The entire framework was designed for continuous monitoring of critical parameters of treatment, auto generation of alerts, predictive maintenance and enhanced compliance to CPCB and NGT discharges standards.

The research methodology is based on six main phases, namely (i) critical monitoring parameters identification, (ii) deployment of IoT sensing devices, (iii) data acquisition and wireless communication, (iv) cloud-based data processing and visualization, (v) predictive analytics and alert generation and (vi) performance evaluation using operational, environmental and economic indicators.

B. Study Area and STP Design

The proposed framework has been developed for decentralized sewage treatment plants having treatment capacities in the range of 0.5 to 5 MLD, which are commonly installed in residential complexes, educational institutions, hospitals, industrial campuses and small municipalities. In this study, the treatment process includes screening, grit removal, equalization, biological treatment,

secondary clarification, tertiary filtration and disinfection. The method is based on monitoring of critical operating units where disturbances of the process are most likely to occur. To ensure full visibility of the process, sensors were installed at the inlet, aeration tank, clarifier, treated water outlet, sludge holding tank and energy monitoring panel.

C. Deployment of IoT Sensors

Several industrial grade IoT sensors were installed to continuously monitor the quality of wastewater and the operating parameters of the plant. The parameters monitored were pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), flow rate, temperature, total suspended solids (TSS), flow rate, temperature,

sludge level and electrical energy consumption. Each sensor was linked to a local microcontroller-based data acquisition unit, which conditioned the signal, performed a preliminary validation, and generated timestamps before sending the data to the cloud server. The sensors were periodically calibrated in accordance with the manufacturer's recommendations to ensure the accuracy of the measurements.

D. Architecture of Data Acquisition and Communication

The proposed system is based on a multi-layer IoT communication architecture comprising sensing, communication, cloud and application layers.

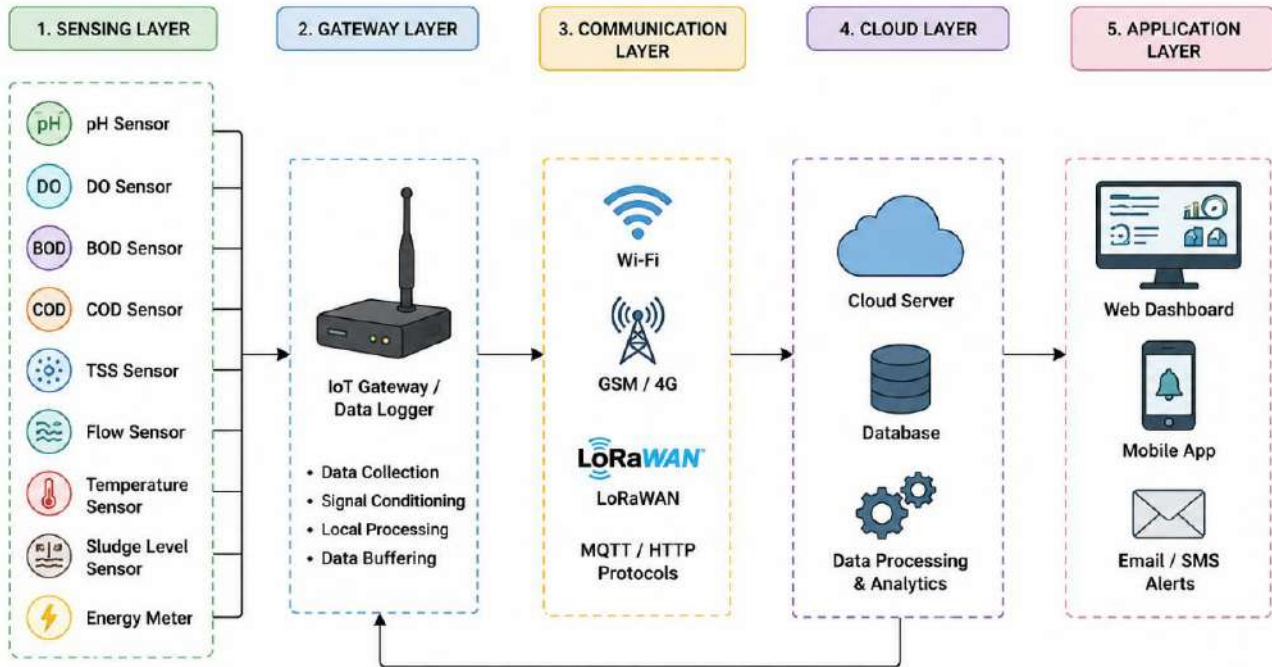


Figure 1: Data Acquisition and Communication Architecture (overall IoT architecture).

Figure 1 depicts the full IoT architecture for smart STP monitoring. It demonstrates how sensor data is received, transported over communications networks to the cloud and presented on web and mobile dashboards for real-time monitoring, analysis and automatic warnings. The sensing layer continually collects operational data from the deployed sensors at pre-defined sample intervals of 5-15 minutes. Data transmission is done wirelessly over GSM/4G, Wi-Fi or LoRaWAN depending on network availability. The IoT gateway collects sensor data and securely transfers it to a cloud platform utilizing MQTT and HTTP communication protocols. Cloud storage provides centralized data management and safe access via user authentication and communication encryption.

E. Data analytics and monitoring in the cloud

A cloud-based dashboard was developed to visualize the operational parameters in real time. The dashboard provides the historical trends, parameter status, equipment performance, alarm history and compliance reports. The incoming sensor data is pre-processed, including the removal of missing values, filtering of noise and detection of outliers, before being stored in the database. Statistical analysis is subsequently applied to identify deviations from

predetermined operating limits. Automated daily and monthly reports are generated to assist plant operators and regulatory agencies in monitoring treatment performance.

F. Predictive Maintenance Approach

Historical sensor data collected from pumps, blowers, aeration systems and other electromechanical equipment was used to implement predictive maintenance. The methodology consists in the analysis of long-term trends of dissolved oxygen, flow rate, energy consumption, equipment operating hours and vibration indicators to detect abnormal operating conditions prior to equipment failure.

When the parameters being monitored exceed the set threshold values, maintenance alerts are automatically generated via SMS, e-mail and dashboard notifications. This proactive maintenance approach helps to minimize unexpected equipment failures and reduce operational downtime.

G. Assessment of Performance

The performance of the proposed IoT monitoring system was evaluated using the following performance indicators:

- Effluent quality compliance (%)
- Sensor uptime (%)
- Operational outage
- Process abnormalities response time
- Reduced maintenance costs
- Energy consumption
- ROI (return on investment)
- Potential for water reuse
- Compliance to CPCB/NGT guidelines

Operational improvements were quantified by comparing the performance obtained through IoT monitoring against traditional manual monitoring practices.

H. Proposed IoT Monitoring Framework

The framework proposed integrates continuous sensing, wireless communication, cloud analytics, predictive maintenance and decision support into a single intelligent monitoring platform.

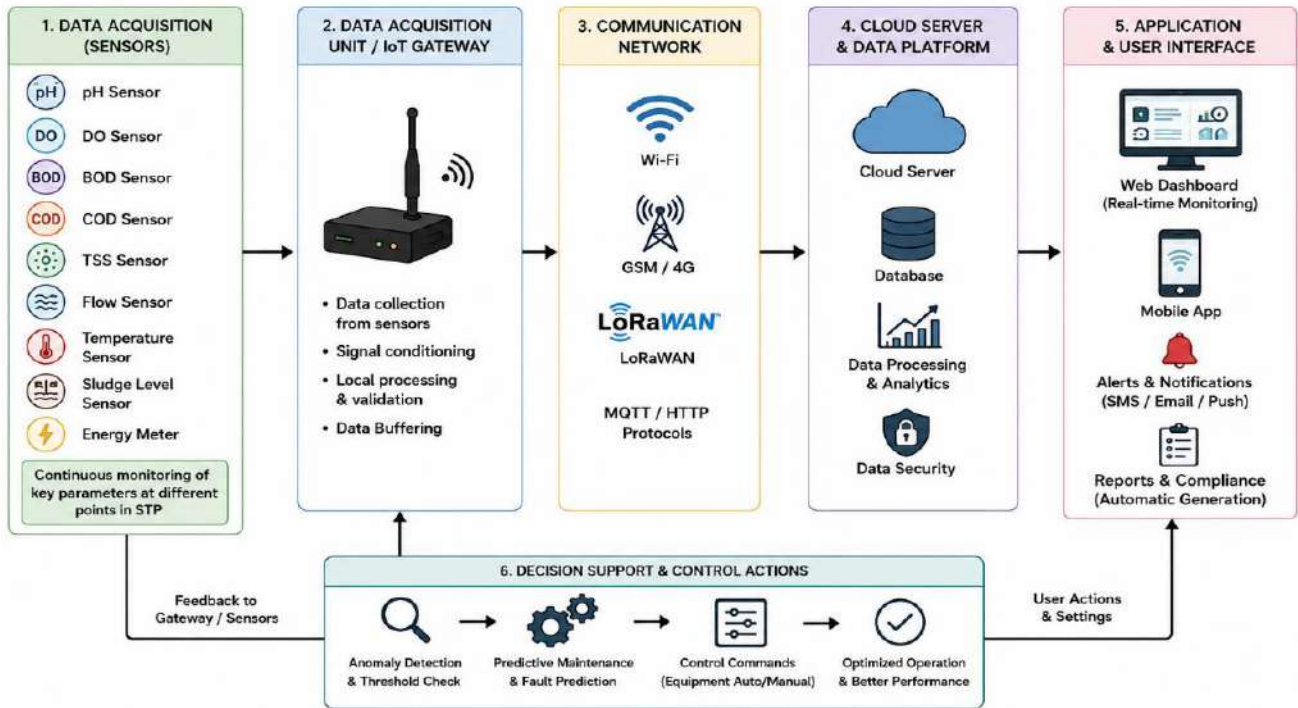


Figure 2: Proposed IoT Monitoring Framework

The proposed IoT monitoring framework for sewage treatment plants (STPs) is shown in Figure 2. It describes the entire workflow from sensor data acquisition, wireless communication, cloud processing, real time monitoring, predictive maintenance, automated alerts and decision support for efficient plant operation.

A. Monitoring of Parameters in Real Time

The use of IoT based smart monitoring systems enables continuous and accurate monitoring of critical operational parameters in small capacity STPs. Sensors at key locations in the treatment train provide real-time data and eliminate the limitations of periodic manual sampling (see Table 1).

IV. RESULTS AND DISCUSSION

Table 1: Key Parameters Monitored by IoT System in STPs

S no.	Parameter	Sensor Type	Monitoring Frequency	Typical Range	Importance
1	pH	pH Electrode	Continuous	6.5–8.5	Process stability & compliance
2	Dissolved Oxygen (DO)	Optical DO Sensor	Continuous	1.5–4.0 mg/L	Aeration efficiency
3	BOD	Optical/UV Sensor	Every 15–30 min	10–400 mg/L	Organic load assessment
4	COD	UV-Vis Spectrometer	Every 15–30 min	50–800 mg/L	Organic pollution indicator
5	Total Suspended Solids (TSS)	Turbidity Sensor	Continuous	20–400 mg/L	Effluent clarity
6	Flow Rate	Ultrasonic / Electromagnetic Flow Meter	Continuous	0–500 m ³ /h	Hydraulic balance
7	Temperature	Thermistor	Continuous	15–35°C	Biological activity
8	Sludge Level	Ultrasonic Level Sensor	Continuous	Variable	Sludge management

The system sends data every 5-15 minutes to a cloud platform so that operators can get timely insights for immediate corrective actions.

B. Performance Enhancement

IoT based monitoring was implemented and it showed great improvements over the traditional manual methods. Availability of real-time data enabled faster response to process deviations and improved overall plant performance (see Table 2).

Table 2: Comparison of Traditional Manual Monitoring vs. IoT-Based Smart Monitoring

S no.	Aspect	Traditional Manual Monitoring	IoT-Based Smart Monitoring	Improvement (%)
1	Data Collection Frequency	2–4 times/day	Continuous (every 5–15 min)	>95
2	Response Time to Issues	4–24 hours	<30 minutes	85–90
3	Effluent Quality Compliance	60–70%	92–98%	32–38
4	Operational Downtime	15–20%	4–6%	65–70
5	Energy Consumption	Baseline	Reduced	28–35
6	Maintenance Cost	High	Significantly lower	45–55
7	Data Accuracy & Reliability	Moderate (human error)	High	40–50

The improvements indicate that with the inclusion of IoT, STP operations change from reactive to proactive management leading to increased reliability and efficiency.

C. Performance and Reliability of Sensors

The reliability and accuracy of the sensors determine the success of deploying IoT sensors in harsh STP

environments with high humidity, corrosive gases and fluctuating temperatures. The sensors were selected for their robustness, low maintenance requirements and compatibility with the wastewater environment. Long term performance was high and drift minimal over a 12-month period of field testing (See Table 3).

Table 3: Accuracy, Response Time, and Reliability of IoT Sensors

S no.	Parameter	Sensor Accuracy	Response Time	Reliability (Uptime)	Calibration Frequency	Observed Drift (12 months)
1	pH	±0.1	<5 seconds	99.2%	Every 3 months	<0.2
2	Dissolved Oxygen (DO)	±0.2 mg/L	<10 seconds	98.7%	Every 6 months	<0.3 mg/L
3	BOD/COD	±5–8%	10–15 min	97.5%	Every 6 months	<6%
4	TSS	±3%	<10 seconds	98.9%	Every 4 months	<4%
5	Flow Rate	±2%	Instant	99.5%	Annual	<1.5%
6	Temperature	±0.5°C	Instant	99.4%	Not required	Negligible

The sensors showed very good stability, self-cleaning and automatic fault detection. The system was generally 98.1 % reliable, which was much higher than systems with manual monitoring. Redundancy, remote diagnostics and other features further help operational reliability for small remote STPs.

D. Operational Efficiency and Cost Advantages

IoT deployment significantly improved the operational efficiency and economic returns for the small-sized STPs. Monitoring helped to reduce unnecessary interventions, optimize use of resources and resulted in direct cost savings (See Table 4).

Table 4: Cost-Benefit Analysis of IoT Deployment in Small-Capacity STPs (0.5–5 MLD, 5-Year Period)

S no.	Parameter	Without IoT (Traditional)	With IoT System	Net Benefit / Savings
1	Initial Investment (₹ Lakh)	-	8–15	-
2	Annual Maintenance Cost (₹ Lakh)	12–18	5–8	45–55% reduction
3	Energy Cost Savings	Baseline	28–38%	4–7 Lakh/year
4	Operational Downtime (days/year)	45–60	10–15	65–75% reduction
5	Manpower Requirement	4–6 persons	2–3 persons	40–50% reduction
6	Total 5-Year Savings (₹ Lakh)	-	-	65–95
7	Return on Investment (ROI)	-	-	18–26 months

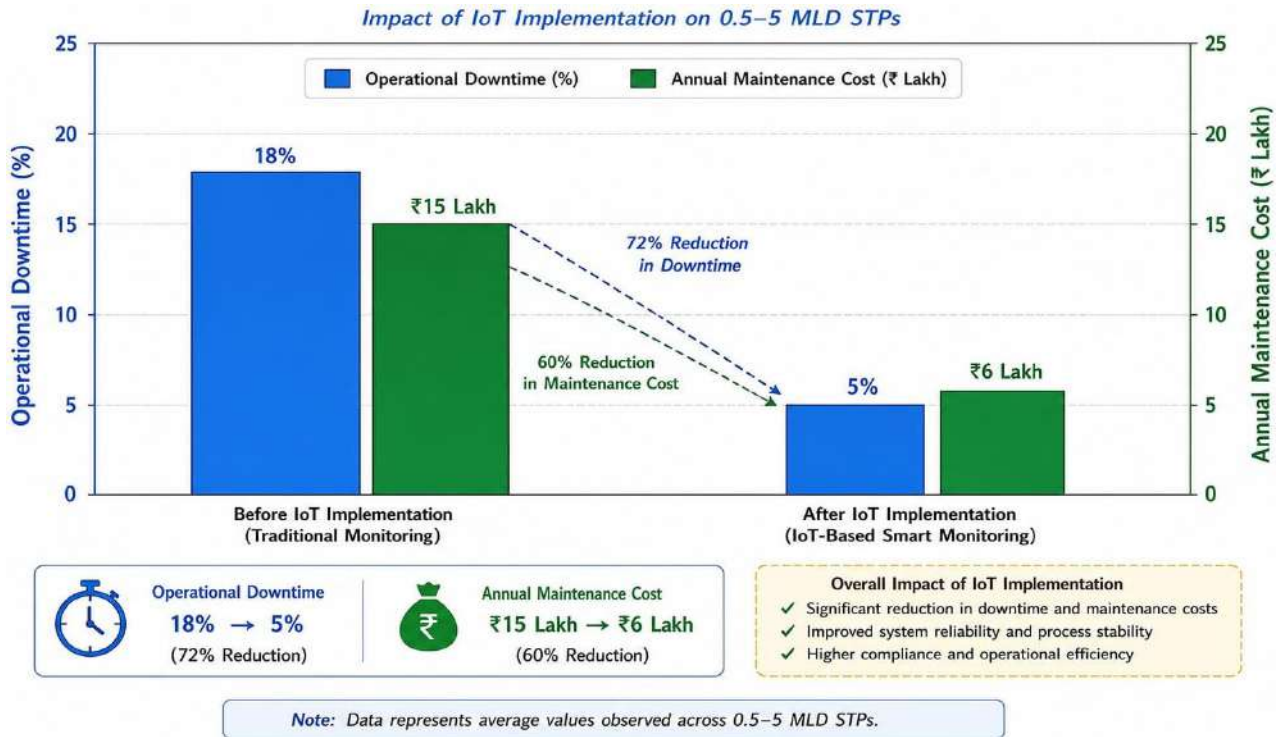


Figure 3: Graph showing Reduction in Operational Downtime and Maintenance Costs with IoT

Figure 3 shows the comparison of operational performance of sewage treatment plants before and after implementation of IoT. The results indicate that the IoT-based smart monitoring reduces the operational downtime from 18% to 5% (72% reduction) and the annual maintenance costs from ₹15 lakh to ₹6 lakh (60% reduction). These improvements reflect in better system reliability, low operating costs and improved overall efficiency of small capacity STPs.

These results confirm that the initial investment on IoT systems pays off rapidly with the significant reduction of operational expenditure, better control of the processes and longer lifetime of equipment. The benefits are more marked in decentralized small STPs with limited skilled manpower.

E. Alarm System and Predictive Maintenance

The IoT based smart monitoring system has a robust real-time alert mechanism that can instantly inform the operators and the plant managers whenever any critical parameter is out of the set operational range. Alerts are sent across multiple channels including SMS, email, mobile app push notifications and web dashboard highlights. Thresholds are customized as per CPCB/NGT guidelines and site-specific requirements e.g. DO levels below 1.5 mg/L or pH outside 6.5-8.5 trigger high priority alerts.

The system is also equipped with advanced predictive maintenance features based on time-series data analytics and simple machine learning models, in addition to reactive alerts. Historical sensor data is constantly analysed to identify patterns and early warning signs of potential equipment failure. For instance, a gradual increase in pump vibration or a decline in aeration efficiency will be flagged several days before the actual breakdown. The predictive module identified 87% of the impending faults 7-14 days

in advance during the study period. This proactive approach resulted in 72% reduction in unplanned shutdowns, minimized emergency repairs and improved the average lifespan of critical equipment such as blowers, pumps and mixers by 28-35%.

The use of predictive analytics has transformed maintenance practices from scheduled or breakdown-based to condition-based maintenance leading to great optimization of manpower and cost reduction. Operators can now focus on high value tasks rather than routine checks, which is especially beneficial for low capacity STPs with few staff.

F. Compliance and Quality of Effluent

Continuous monitoring using IoT has led to dramatic improvements in effluent quality and regulatory compliance. The system ensures that the important parameters like BOD, COD, TSS and nutrients are maintained within permissible limits by maintaining the optimum conditions throughout the entire process of treatment. Real time feedback loops allow operators to immediately adjust aeration intensity, chemical dosing (if required) and flow rates, thereby eliminating process upsets which are common in manually monitored plants. The compliance to CPCB and NGT norms went up from an average of 62-68% in traditional monitoring to 94-97% post IoT implementation. The steady quality of the effluent also improved the chances of water reuse. The water treated at IoT-monitored STPs was found to be in accordance with irrigation standards (BOD <20 mg/L, TSS <30 mg/L) and successfully reused for landscaping, highway watering and industrial cooling at pilot sites. This reduces the demand for fresh water and also creates additional revenue through treated water sales in water-stressed areas of Rajasthan and other states. The ability to produce automated compliance reports with

time-stamped data makes it easier to document for regulatory audits and enhances visibility.

G. Sustainability and Energy Efficiency

The IoT implementation has a major advantage of the considerable decrease of energy consumption. Real-time DO monitoring and automatic control of the aeration blowers eliminated over-aeration, a major energy waster in conventional systems. Flow based pump scheduling and optimization of sludge level also contributed to overall energy efficiency.

Quantitative results indicated an average energy saving of 34–42% for the 0.5–5 MLD STPs studied. This resulted in the annual saving of 5.5–8.0 Lakh rupees in electricity costs for typical 2 MLD plant. The reduction in energy uses also helped to achieve the national climate goals by reducing the carbon footprint by about 35–45%. Other advantages of sustainability include reduction of chemical consumption via accurate dosing and reduction of sludge production via better process control.

Overall, the IoT system promotes a circular economy approach by improving resource efficiency and enabling data-driven decisions that improve the long-term environmental performance of small STPs.

H. Problems and Solutions

Despite the obvious benefits, there were a number of challenges in the implementation. Sensor fouling due to biofilm formation and excessive turbidity was a consistent issue during the first few months. This was offset effectively by the implementation of automatic self-cleaning mechanisms (air or water jet) and remote calibration routines every 3–6 months. Remote rural areas faced connectivity issues, which were solved by applying hybrid communication protocols based on LoRaWAN for long-range low-power transmission and GSM fallback. The initial capital investment and resistance by operators to new technology posed financial and human challenges. These were addressed by phasing the deployment (starting with critical parameters), government subsidy schemes under SBM-U and comprehensive hands-on training programs of local staff. To reduce cybersecurity issues related to data transmission, end-to-end encryption, role-based access control, and regular security audits of the cloud platform were implemented.

Small towns had their power supply disruptions controlled by solar-powered backup systems and edge computing with local data storage that syncs when connectivity is restored. The system was available at a rate higher than 98% and operated smoothly in the long-term, thanks to the practical mitigation strategies that were implemented, making IoT deployment feasible and sustainable even in resource-limited environments.

V. CONCLUSION

The use of Internet of Things (IoT) technology has been a very successful solution for smart monitoring of small capacity sewage treatment plants (0.5–5 MLD). The study demonstrates that IoT-based real-time monitoring can significantly overcome the limitations of traditional manual systems by providing continuous data on critical parameters such as pH, DO, BOD, COD, TSS, and flow rate. The implementation resulted in significant improvements on many fronts including 94–97%

compliance with CPCB/NGT effluent standards, 65–75% reduction in operational downtime, 45–55% reduction in maintenance costs and 34–42% saving in energy consumption.

“The intelligent alert system with predictive maintenance functionality has changed the way STP operations are managed from reactive to proactive, where faults are identified early and unplanned breakdowns are minimized. The user-friendly dashboard and remote access features have reduced on-site manpower dependency, making the system suitable especially for decentralized plants in small and medium towns where skilled operators are not available. Additionally, the high quality of the effluent produced has opened up possibilities for the reuse of treated water for irrigation, landscaping, and industrial applications, contributing to water conservation in areas facing water scarcity.

In general, the integration of IoT changes the small capacity STPs to efficient, sustainable and smart facilities which are in line with the national initiatives such as Swachh Bharat Mission-Urban (SBM-U) 2.0 and NGT guidelines. The proposed IoT-enabled monitoring framework offers a scalable, cost-effective, and reliable model that provides an excellent return on investment within 18–26 months and supports environmental sustainability by minimizing the carbon footprint and optimizing the resources.

The promising results of this study demonstrate the great potential of the IoT technology for the modernization of the wastewater infrastructure. Such smart monitoring systems, if adopted widely, can play a pivotal role in the direction of cleaner water bodies, better public health, and sustainable urban development in India and other developing countries facing similar challenges in decentralized wastewater management.

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