iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** VII **Month of publication:** July 2026

DOI: https://doi.org/10.22214/ijraset.2026.84427

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VII July 2026- Available at www.ijraset.com

Wastewater Treatment and Reuse in Urban area

Panduru Suresh[1], Prof. BKR Pattnaik[2]
[1]*Master of Technology in Environmental Engineering*
[2]*Supervisor, Gandhi Institute for Technology (GIFT), Autonomous*
Bhubaneswar, Biju Patnaik University Of Technology Rourkela, Odisha

Abstract: Rapid urbanization and industrial growth in Jamnagar have significantly increased the generation of municipal wastewater, posing serious environmental and public health concerns. Jamnagar, a prominent industrial and coastal city in Gujarat, faces increasing pressure on freshwater resources due to population growth, industrial expansion, and climate variability. Effective wastewater treatment and reuse have therefore become essential components of sustainable urban water management.

This thesis presents a comprehensive technical assessment of wastewater generation, treatment infrastructure, and reuse potential for Jamnagar City. The study evaluates existing sewerage networks, treatment plant capacities, influent and effluent quality parameters, and operational efficiencies. Advanced and conventional treatment technologies such as Activated Sludge Process (ASP), Sequential Batch Reactor (SBR), Membrane Bioreactor (MBR), and tertiary treatment options are critically analyzed for their suitability under local conditions.

A reuse framework is developed focusing on industrial reuse, agricultural irrigation, urban landscaping, groundwater recharge, and non-potable municipal applications. Economic evaluation includes capital expenditure (CAPEX), operational expenditure (OPEX), lifecycle cost assessment, and cost-benefit analysis of reuse implementation. Environmental impact assessment highlights reductions in freshwater abstraction, nutrient load discharge, and greenhouse gas emissions.

The study concludes with a phased implementation roadmap aligned with national guidelines issued by the Central Pollution Control Board (CPCB) and Gujarat Pollution Control Board (GPCB). The proposed strategy promotes wastewater as a valuable resource rather than waste, contributing to circular economy principles, climate resilience, and sustainable urban development.

I. INTRODUCTION

Water is one of the most critical natural resources essential for sustaining life, economic development, and ecological balance. With rapid urbanization, industrialization, and population growth, global water demand has increased significantly, while freshwater availability continues to decline. According to the United Nations, nearly **40% of the world's population faces water scarcity**, and this percentage is projected to rise in the coming decades. In developing countries like India, the situation is particularly alarming due to uneven rainfall distribution, over-extraction of groundwater, and poor management of water resources.

Wastewater generation is an inevitable by-product of domestic, commercial, industrial, and agricultural activities. Traditionally, wastewater was considered a waste material that needed disposal. However, with evolving environmental concerns and technological advancements, wastewater is now increasingly viewed as a **valuable resource** that can be treated and reused for multiple purposes. Properly designed wastewater treatment systems can help conserve freshwater resources, reduce pollution loads on natural water bodies, and promote sustainable development.

The increasing need for sustainable water management practices has led to the widespread adoption of wastewater treatment and reuse systems. Governments, municipalities, industries, and residential communities are now embracing modern treatment technologies to ensure compliance with environmental standards while maximizing reuse potential.

In India, the Central Pollution Control Board (CPCB) and Bureau of Indian Standards (BIS) have established strict guidelines for wastewater discharge and reuse. However, a large portion of wastewater—especially from urban and semi-urban areas—still remains untreated and is discharged into rivers, lakes, and groundwater systems, causing severe environmental degradation. Therefore, designing efficient wastewater treatment plants (WWTPs) is essential not only to manage waste but also to harness it as an alternative water source.

Water is a fundamental natural resource that underpins human survival, economic progress, and environmental stability. In recent decades, the growing pressures of urbanization, industrial expansion, and population increase have placed immense stress on available freshwater resources. As cities expand and industrial activities intensify, the demand for water has risen sharply, often exceeding the rate at which natural systems can replenish it.

This imbalance has led to widespread water scarcity, particularly in developing nations such as India, where uneven rainfall patterns, excessive groundwater extraction, and inadequate water management practices further aggravate the problem. The increasing gap between water demand and supply highlights the urgent need for sustainable solutions that can ensure long- term water security while maintaining ecological balance.

In this context, wastewater has emerged as a valuable and underutilized resource rather than merely a waste product. Every human activity—whether domestic, commercial, or industrial— generates wastewater that contains both pollutants and reusable water components. Traditionally, such wastewater was disposed of into nearby water bodies with minimal or no treatment, leading to severe environmental pollution and health hazards. However, advancements in treatment technologies and a growing awareness of environmental sustainability have transformed the perception of wastewater. It is now recognized as a potential alternative water source that, when properly treated, can be reused for various non- potable applications such as irrigation, industrial processes, and sanitation. This shift in perspective plays a crucial role in reducing the burden on freshwater resources and minimizing pollution of natural ecosystems.

The present project is developed in response to these emerging challenges and opportunities in water resource management. It focuses on the detailed study and design of an efficient wastewater treatment and reuse system that aligns with modern sustainability principles and regulatory requirements. The project encompasses all major aspects of wastewater engineering, including characterization of influent, selection of appropriate treatment technologies, design of individual treatment units, and effective sludge management strategies. Additionally, it evaluates feasible reuse applications to support the concept of zero discharge and resource conservation. By integrating technical, environmental, and economic considerations, the study aims to provide a comprehensive and practical solution for wastewater management, contributing to sustainable development and improved water resource utilization.

This project report focuses on the comprehensive study, design, and evaluation of a wastewater treatment and reuse system. It covers all essential aspects, including wastewater characterization, selection of treatment technologies, detailed design of treatment units, sludge management, and assessment of feasible reuse options. The report also integrates environmental, economic, and operational considerations to provide a holistic understanding of wastewater treatment processes.

II. LITERATURE REVIEW

The reviewed literature highlights the growing importance of wastewater treatment and reuse as a sustainable solution to global water scarcity and environmental challenges. Early work by Qasim and Zhu (2017) emphasized that wastewater reuse and reclamation can significantly enhance water availability while simultaneously conserving environmental resources and supporting agricultural productivity. Building on this perspective, Reymond et al. (2020) demonstrated through an Indian case study that effective governance frameworks play a crucial role in improving wastewater collection, treatment, and its reintegration into the water cycle, while also maintaining affordability for users.

A landmark study by Tchobanoglous and co-researchers (2003) provided a comprehensive framework for wastewater engineering, emphasizing the design and operation of primary, secondary, and tertiary treatment systems. The study highlighted the importance of integrated treatment processes for achieving high effluent quality and introduced design guidelines for activated sludge systems, clarifiers, and filtration units. It also stressed the need for combining physical, biological, and chemical processes to meet stringent environmental standards, making it a foundational reference for modern STP design.

A comparative study conducted by Lerner et al. (2007) evaluated the performance of membrane bioreactors (MBR) against conventional activated sludge systems. The research demonstrated that MBR systems produced significantly effluent quality, with suspended solids often reduced to around 1 mg/L compared to higher levels in conventional systems. This study established MBR as a superior option for applications requiring high-quality treated water and reuse potential.

Henze et al. (2008) focused on biological nutrient removal (BNR) processes, particularly nitrogen and phosphorus removal in activated sludge systems. The study demonstrated how modifications such as anaerobic–anoxic–aerobic configurations enhance nutrient removal efficiency. It provided theoretical and practical insights into microbial processes, significantly influencing the design of advanced STPs.

Grady et al. (2011) conducted detailed research on microbial kinetics in biological wastewater treatment systems. The study explained substrate utilization, biomass growth, and system modeling, providing critical insights into optimizing parameters such as F/M ratio and SRT. It contributed to improving process stability and efficiency in activated sludge systems.

The U.S. Environmental Protection Agency (2013) published an extensive evaluation of wastewater treatment technologies, confirming that activated sludge remains the most widely adopted biological treatment method. The report also addressed operational challenges such as sludge bulking and recommended best practices for process optimization and regulatory compliance.

A 2014 study compared activated sludge, SBR, and MBR technologies using long-term operational data. The results indicated that MBR systems achieved higher removal efficiencies and produced high-quality effluent suitable for reuse, while also maintaining stable operation. This study reinforced the importance of advanced technologies in modern wastewater treatment.

Chahal et al. (2016) emphasized the environmental and health impacts of untreated wastewater, particularly highlighting the risks posed by pathogens and heavy metals. The study stressed the need for effective treatment systems to prevent contamination of water bodies and protect public health.

A 2017 study compared multiple biological treatment systems, including conventional activated sludge (CAS), SBR, and MBR. It concluded that while activated sludge remains widely used due to simplicity and cost-effectiveness, advanced systems like MBR offer better effluent quality and compact design.

Wongburi et al. (2018) developed criteria for selecting appropriate wastewater treatment technologies based on performance, cost, and sustainability. The study emphasized the importance of selecting site-specific solutions to achieve optimal treatment efficiency and long-term feasibility.

A comprehensive assessment by the Central Pollution Control Board (2020) highlighted the status of wastewater treatment in India, revealing that a significant portion of sewage remains untreated. The study emphasized the urgent need for improved infrastructure, advanced technologies, and strict regulatory enforcement.

A 2021 study on sequencing batch reactors (SBR) introduced advanced mathematical models to simulate reactive settling and biological processes. The research demonstrated how modeling tools can improve understanding of system behavior and enhance design accuracy for wastewater treatment plants.

A 2022 study compared MBR and SBR technologies for treating industrial wastewater and found that MBR achieved higher BOD removal efficiency (up to 95%) compared to SBR systems. The research highlighted the effectiveness of MBR in handling complex wastewater and achieving superior effluent quality.

A 2022 study published in IRJET analyzed various wastewater treatment technologies and emphasized the importance of selecting appropriate systems based on sustainability, cost, and efficiency. It recommended upgrading traditional systems to meet modern environmental standards.

A recent 2024 study introduced the use of artificial intelligence and deep learning for analyzing activated sludge characteristics. The research demonstrated how image-based analysis can predict sludge settling behavior and prevent operational issues, improving plant efficiency and reliability.

A 2025 review highlighted the advancements in wastewater treatment technologies, including MBBR, MBR, and SBR systems. The study emphasized their efficiency, compact design, and suitability for modern sustainable infrastructure, while reaffirming that activated sludge remains a widely used and reliable method.

Subsequent studies have focused on sector-specific applications and technological advancements. Ashraf et al. (2021) observed that wastewater treatment can substantially reduce excessive water consumption in water-intensive industries such as alcohol breweries. Similarly, Fito and Van Hulle (2021) highlighted that wastewater reclamation can serve as an alternative water source for both agricultural and industrial uses, thereby reducing competition for limited freshwater resources among different sectors. Liao et al. (2021) further noted that the increasing adoption of wastewater reuse is driven by factors such as climate change, rapid urbanization, and the expansion of arid conditions into previously water-abundant regions.

Recent research has also explored innovative treatment technologies and management strategies. Kharraz et al. (2022) investigated the application of membrane distillation bioreactor (MDBR) systems, demonstrating their effectiveness in enhancing wastewater treatment efficiency and enabling water reuse for domestic and agricultural purposes. Additionally, Sharma et al. (2022) emphasized the role of advanced technologies and innovative approaches in improving sludge management and wastewater treatment processes, thereby contributing to overall environmental sustainability. Collectively, these studies underline the critical role of wastewater treatment and reuse in achieving sustainable water management and reducing pressure on natural water resources.

Recent research highlights the growing importance of wastewater reuse as a sustainable strategy for urban water management. A study by Negi (2024) examined multiple wastewater reuse approaches, including direct potable reuse, indirect reuse, and non-potable reuse, using life cycle assessment methods. The findings indicate that centralized non-potable reuse systems offer the lowest environmental impacts in urban settings, particularly in water-stressed regions, making them a viable and sustainable option for cities facing water scarcity.

In urban environments, treated wastewater is increasingly recognized as a valuable alternative water resource. A study published in 2025 emphasized that treated wastewater generated in cities can significantly reduce pressure on freshwater sources. It also highlighted that reuse practices, if properly implemented, can support urban water demand while ensuring environmental protection and long-term sustainability.

Recent advancements in integrated urban water management have demonstrated that wastewater reuse can be effectively incorporated into city planning frameworks. Michalopoulos (2025) emphasized that combining wastewater reuse with governance reforms, green infrastructure, and digital monitoring systems can enhance urban water resilience. The study also highlighted that advanced treatment technologies such as membrane bioreactors and reverse osmosis play a critical role in ensuring safe and reliable reuse of wastewater in urban areas.

Urban wastewater reuse has also been studied in the context of agricultural applications. Assal (2024) investigated the reuse of treated wastewater for irrigation and found that while it offers a sustainable water source, proper treatment is essential to remove contaminants such as heavy metals and pathogens. The study emphasized the need for advanced treatment processes to ensure environmental safety and protect public health.

Technological improvements in wastewater treatment systems have been identified as key drivers of sustainable reuse. Qteishat (2024) evaluated the performance of wastewater treatment plants and found that conventional systems often fail under high load conditions in urban areas. The study concluded that modern treatment technologies significantly improve efficiency, reduce environmental impact, and enhance the potential for wastewater reuse in cities.

Recent studies have also redefined wastewater treatment plants as resource recovery hubs rather than mere disposal facilities. A 2026 study demonstrated that advanced wastewater treatment plants can recover valuable resources such as water, nutrients, and energy. This approach aligns with circular economy principles and supports sustainable urban development by transforming waste into usable resources.

In the Indian context, urban wastewater management remains a significant challenge due to rapid urbanization and inadequate infrastructure. According to a national-level assessment, India generates a large volume of urban wastewater, but only a fraction is treated effectively. The study emphasized the need for improved infrastructure, decentralized treatment systems, and policy interventions to enhance wastewater reuse and achieve sustainable water management.

Integrated urban water management approaches have gained prominence in recent years. A 2025 study highlighted that combining wastewater reuse with recycling and climate-resilient strategies can help cities address water scarcity challenges. Innovative solutions such as constructed wetlands, nanotechnology-based treatment systems, and membrane filtration were identified as effective methods for improving water quality and reuse efficiency.

The concept of circular economy has been increasingly applied to urban wastewater management. Recent research indicates that treated wastewater can be reused not only for irrigation and industrial purposes but also for groundwater recharge and urban landscaping. This approach reduces dependence on freshwater sources and contributes to sustainable resource management in cities.

Another emerging trend in urban wastewater management is the adoption of decentralized treatment systems. These systems are particularly suitable for densely populated urban areas where centralized infrastructure is insufficient. Decentralized systems improve treatment efficiency, reduce transmission losses, and enable localized reuse of wastewater, thereby enhancing overall sustainability and resilience of urban water systems.

III. PROBLEM STATEMENT, OBJECTIVES AND FUTURE SCOPE

A. Problem Statement

Water is a fundamental resource essential for sustaining human life, economic development, and ecological balance. However, rapid population growth, urbanization, industrialization, and changing consumption patterns have significantly increased the demand for freshwater resources. Simultaneously, the volume of wastewater generated from domestic, industrial, and commercial activities has risen substantially. In many developing regions, the available freshwater resources are insufficient to meet this growing demand, resulting in severe water stress and resource depletion.

A major concern associated with this imbalance is the inadequate management of wastewater. A significant proportion of wastewater generated in urban areas is discharged untreated or partially treated into natural water bodies such as rivers, lakes, and land surfaces. This practice leads to severe environmental degradation, including water pollution, ecosystem damage, and loss of biodiversity. Contaminated water sources pose serious public health risks by spreading waterborne diseases and exposing populations to harmful pathogens and toxic substances. Furthermore, untreated wastewater can infiltrate groundwater systems, leading to long-term contamination of drinking water sources.

Another critical issue is the underutilization of wastewater as a potential resource. Treated wastewater can serve as an alternative water source for applications such as irrigation, industrial processes, landscaping, flushing, and groundwater recharge. However, due to the lack of proper infrastructure, technological limitations, financial constraints, and insufficient policy implementation, wastewater reuse remains limited in many regions. As a result, large volumes of potentially reusable water are wasted, increasing pressure on already scarce freshwater resources.

In addition, existing wastewater treatment infrastructure is often outdated, inefficient, or incapable of handling the current load. Poor planning, inadequate monitoring systems, and lack of awareness among stakeholders further hinder effective wastewater management. Sludge management also remains a challenge, often leading to secondary pollution problems.

Therefore, the core problem lies in the absence of an efficient, integrated, and sustainable wastewater treatment and reuse system. This has resulted in increased environmental pollution, depletion of freshwater resources, and heightened public health risks. Addressing this issue requires a systematic approach to wastewater treatment, resource recovery, and reuse within a sustainable water management framework.

B. Objectives of the Study

The present study aims to develop a systematic and sustainable approach for wastewater treatment and reuse by evaluating wastewater characteristics, designing efficient treatment systems, and identifying suitable reuse applications. It focuses on reducing pollution levels, conserving freshwater resources, and promoting environmentally sustainable water management practices.

Key Objectives:

- To analyze the quantity and quality of wastewater from urban and industrial sources
- To identify physical, chemical, and biological characteristics of wastewater
- To design an efficient treatment system (primary, secondary, and advanced processes)
- To explore reuse options such as irrigation, industrial use, landscaping, and groundwater recharge
- To identify gaps in existing wastewater management practices
- To recommend improvements for sustainable and efficient wastewater management
- To promote a circular water economy and reduce dependence on freshwater resources

The primary objective of this study is to carry out a comprehensive analysis of the quantity and quality of wastewater generated from urban and industrial sources, recognizing that accurate assessment of flow rates and pollutant loads forms the foundation for effective treatment system design. This involves evaluating the physical, chemical, and biological characteristics of wastewater, including parameters such as suspended solids, organic matter content (BOD and COD), nutrients, and microbial contamination. Understanding these characteristics is essential for selecting appropriate treatment technologies and ensuring that the system can handle varying influent conditions. Based on this analysis, the study aims to design an efficient and integrated wastewater treatment system comprising primary, secondary, and advanced treatment processes. Each stage is carefully planned to progressively remove contaminants and achieve the desired effluent quality, ensuring compliance with environmental standards and suitability for reuse.

In addition to treatment design, the study also focuses on exploring feasible and sustainable reuse options for treated wastewater. These include applications such as irrigation, industrial processes, landscaping, and groundwater recharge, all of which contribute to reducing the demand for freshwater resources. By promoting the concept of wastewater reuse, the study supports the idea of transforming wastewater from a disposal problem into a valuable resource. Furthermore, the research seeks to identify gaps and limitations in existing wastewater management practices, particularly in terms of treatment efficiency, infrastructure inadequacies, and lack of reuse strategies. Recognizing these gaps is crucial for proposing practical and effective improvements that enhance overall system performance and sustainability.

Another important objective of the study is to recommend strategies for improving wastewater management practices in a manner that is both environmentally sustainable and economically viable. This includes the adoption of advanced treatment technologies, efficient sludge management, and integration of monitoring and control systems. The study also emphasizes the importance of promoting a circular water economy, where water is reused and recycled within the system rather than being discharged as waste. By reducing dependence on limited freshwater resources and minimizing environmental pollution, the proposed approach contributes to long- term water security and sustainable development. Overall, the objectives of the study are aligned with modern environmental goals, aiming to create a holistic, efficient, and sustainable wastewater management framework.

C. Future Scope

The scope for future work in wastewater treatment and reuse is extensive, particularly in the context of increasing urbanization and climate change. One important area of future research is the integration of advanced and emerging treatment technologies such as membrane bioreactors, nanotechnology-based filtration systems, and artificial intelligence-based monitoring systems. These technologies have the potential to improve treatment efficiency, reduce operational costs, and enhance system reliability.

Another significant area of future scope lies in the development of decentralized wastewater treatment systems. Such systems can be particularly effective in densely populated urban areas where centralized infrastructure is insufficient. Decentralized systems enable localized treatment and reuse, reducing transmission losses and improving overall efficiency.

Future research can also focus on strengthening policy frameworks and governance mechanisms for wastewater reuse. This includes developing guidelines, standards, and incentives to promote the adoption of reuse practices across different sectors. Public awareness and stakeholder participation will play a crucial role in ensuring the successful implementation of such initiatives.

Additionally, the concept of circular economy in water management offers significant potential for future development. Wastewater treatment plants can be transformed into resource recovery facilities that generate not only treated water but also energy, nutrients, and reusable by-products. This approach can contribute to sustainable urban development and resource conservation.

Finally, future studies can explore the long-term environmental and economic benefits of wastewater reuse systems through real-world case studies and performance evaluations. Such research will help in developing scalable and sustainable solutions for water management challenges.

D. Limitations of the Study

Although comprehensive, the study is subject to certain limitations:

1) The scope is limited to domestic wastewater; industrial wastewater with toxic constituents is not included.
2) Field data collection may be constrained by seasonal variations in wastewater characteristics.
3) Financial estimates may vary depending on market fluctuations and regional costs.
4) Detailed advanced modelling (CFD, ASM models) is not included unless specifically required
5) Actual implementation and long-term performance monitoring are beyond the scope of this academic study.

The present study is subject to certain limitations that must be acknowledged while interpreting its findings and applicability. Firstly, the scope of the study is confined primarily to domestic wastewater, and it does not consider industrial wastewater containing toxic or hazardous constituents. Industrial effluents often include complex chemicals, heavy metals, and non-biodegradable substances that require specialized treatment processes beyond conventional sewage treatment methods. Therefore, the design and analysis presented in this study are not intended for such complex wastewater streams. Additionally, the accuracy of field data used for analysis may be influenced by **seasonal variations** in wastewater characteristics. Factors such as rainfall, temperature changes, and fluctuations in water usage patterns can alter both the quantity and quality of wastewater, potentially affecting the reliability of the collected data and the subsequent design assumptions.

Another important limitation relates to the financial estimation and cost analysis associated with the proposed Sewage Treatment Plant. The cost calculations provided in the study are based on standard assumptions and available data; however, actual costs may vary significantly due to market fluctuations, regional price differences, labor costs, and material availability. These variations can impact the overall feasibility and economic evaluation of the project. Furthermore, the study does not incorporate advanced computational modeling techniques such as Computational Fluid Dynamics (CFD) or Activated Sludge Models (ASM), which are often used for detailed simulation and optimization of treatment processes. While these tools can provide more precise insights into system behavior, their exclusion in this academic study is due to constraints related to time, resources, and the intended scope of the project.

Finally, the study is primarily focused on the design and theoretical evaluation of the wastewater treatment system and does not extend to actual implementation or long-term operational monitoring. Practical challenges that may arise during construction, commissioning, and operation—such as equipment performance issues, maintenance requirements, and operational inefficiencies—are beyond the scope of this work. Similarly, long-term performance assessment, including system durability, efficiency under varying conditions, and lifecycle analysis, is not covered. As a result, while the study provides a comprehensive and well-structured design framework, its real-world applicability may require further validation through pilot studies, field implementation, and continuous monitoring to ensure sustained performance and reliability.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VII July 2026- Available at www.ijraset.com

IV. CASE STUDY

A. Description of Study Area

The present study considers Jamnagar as the case study area for evaluating wastewater treatment and reuse potential in urban environments. Jamnagar is located in the western part of the state of Gujarat and serves as an important industrial, commercial, and cultural hub of the Saurashtra region. The city has experienced rapid urbanization driven by industrial expansion, petroleum refining activities, and infrastructural development. This growth has significantly increased the demand for water and consequently led to a substantial rise in wastewater generation.

Geographically, Jamnagar is situated at approximately 22.47° N latitude and 70.07° E longitude, with an average elevation of about 15 meters above mean sea level. The city lies near the Gulf of Kutch and experiences a semi-arid climate characterized by high summer temperatures reaching up to 42°C, moderate winters, and an average annual rainfall of about 500–600 mm. These climatic conditions result in limited availability of freshwater resources and high evaporation losses, thereby intensifying the need for efficient water management practices.

Administratively, the city is governed by the Jamnagar Municipal Corporation (JMC), which is responsible for managing water supply, sewerage systems, drainage, and solid waste management. The urban infrastructure is divided into several administrative wards to facilitate efficient service delivery. The current water supply in the city is approximately 135 liters per capita per day (LPCD), and nearly 80% of this supplied water is converted into wastewater. The estimated wastewater generation ranges between 95–110 million liters per day (MLD), with projections indicating an increase to around 130 MLD by the year 2045.

However, the existing wastewater treatment infrastructure is insufficient to handle the increasing load, resulting in a significant treatment gap. This scenario justifies the need for improved treatment facilities and effective reuse strategies. Due to limited freshwater availability and increasing demand, wastewater reuse has become essential in Jamnagar for applications such as industrial cooling, landscaping, agricultural irrigation, and construction activities.

The selection of Jamnagar as the case study area is justified by its rapid urban growth, high industrial water demand, increasing wastewater generation, and significant potential for implementing large-scale wastewater reuse systems. Additionally, supportive policies at the state level further strengthen the feasibility of adopting sustainable wastewater management practices in the region.

V. RESEARCH AREA OF FOCUS

A. Wastewater Characteristics and Treatment Focus

The research area of this study focuses on understanding wastewater characteristics and their implications for the design and operation of treatment systems. Wastewater generated in urban areas is a complex mixture of domestic sewage, industrial effluents, and stormwater infiltration. The characteristics of wastewater vary depending on factors such as population density, water consumption patterns, climatic conditions, and the presence of industrial activities.

The study emphasizes the classification of wastewater characteristics into physical, chemical, and biological parameters. Physical characteristics such as color, odour, temperature, turbidity, and total suspended solids provide information about the general condition of wastewater. Chemical characteristics, including pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), nutrients, chlorides, and oil and grease, indicate the pollution strength and organic load of wastewater. Biological characteristics focus on the presence of microorganisms and pathogens, which are critical for determining treatment requirements and public health risks.

Understanding these characteristics is essential for selecting appropriate treatment technologies and designing efficient treatment units. The study also considers factors affecting wastewater quality, such as population growth, industrial discharges, and climatic conditions. Accurate sampling methods, including grab and composite sampling, are emphasized to ensure reliable analysis of wastewater parameters.

Furthermore, the research focuses on laboratory analysis techniques used to evaluate wastewater quality, such as BOD testing, COD analysis, TSS measurement, and microbial assessment. Interpretation of these results helps in determining the strength of wastewater and identifying suitable treatment processes.

Overall, the research area is centered on developing a scientific understanding of wastewater properties and applying this knowledge to design effective treatment and reuse systems. This approach supports sustainable water management by reducing pollution, improving treatment efficiency, and enabling safe reuse of treated wastewater in urban environments.

Table 1: Typical Domestic Wastewater Characteristics Table

Parameter	Unit	Typical Range
pH	–	6.5 – 8.5
BOD_5	mg/L	200 – 350
COD	mg/L	400 – 600
TSS	mg/L	150 – 300
TDS	mg/L	300 – 700
Total Nitrogen	mg/L	20 – 80
Ammonia N	mg/L	10 – 40
Total Phosphorus	mg/L	4 – 10
Chlorides	mg/L	50 – 150
Oil & Grease	mg/L	50 – 150
Temperature	°C	25 – 35

The table presents the typical characteristics of domestic wastewater, which are essential for understanding treatment requirements and designing an efficient Sewage Treatment Plant (STP). One of the most important parameters is pH, which typically ranges from 6.5 to 8.5, indicating that domestic wastewater is generally neutral to slightly alkaline. Maintaining this range is crucial because biological treatment processes rely on microorganisms that are sensitive to extreme pH conditions. The Biochemical Oxygen Demand (BOD_5), ranging from 200 to 350 mg/L, represents the amount of biodegradable organic matter present in the wastewater. High BOD values indicate a strong organic load, requiring efficient biological treatment. Similarly, Chemical Oxygen Demand (COD), ranging from 400 to 600 mg/L, measures the total amount of oxygen required to oxidize both biodegradable and non-biodegradable organic matter. COD is always higher than BOD, and together they provide a comprehensive understanding of organic pollution levels. Total Suspended Solids (TSS), typically between 150 and 300 mg/L, indicate the presence of particulate matter such as organic debris, silt, and microorganisms, which must be removed through sedimentation and filtration processes.

Another set of parameters in the table relates to dissolved substances and nutrients present in wastewater. Total Dissolved Solids (TDS), ranging from 300 to 700 mg/L, represent inorganic salts and small amounts of organic matter dissolved in water. While moderate TDS levels are acceptable, higher concentrations can affect reuse suitability, especially for irrigation. Nutrient parameters such as Total Nitrogen (20–80 mg/L) and Ammonia Nitrogen (10–40 mg/L) are critical because excessive nitrogen can lead to eutrophication in receiving water bodies. Biological processes such as nitrification and denitrification are required to remove nitrogen effectively. Similarly, Total Phosphorus (4–10 mg/L) contributes to algal growth and must be controlled through biological or chemical treatment methods. Chlorides (50–150 mg/L) are generally present due to domestic activities and indicate the salinity of wastewater; while not directly harmful at moderate levels, high concentrations can affect plant growth when reused for irrigation.

The remaining parameters include Oil & Grease (50–150 mg/L) and temperature (25–35°C), both of which significantly influence treatment efficiency. Oil and grease originate from kitchen waste, food processing, and domestic activities, and they can form a floating layer that interferes with oxygen transfer in biological treatment units. Therefore, their removal in preliminary treatment stages such as skimming tanks or grease traps is essential. Temperature, typically ranging between 25°C and 35°C in tropical regions, plays a vital role in biological activity, as higher temperatures generally enhance microbial metabolism and reaction rates. However, excessively high temperatures can inhibit microbial growth and reduce treatment efficiency. Overall, these parameters collectively define the strength and characteristics of domestic wastewater and serve as the basis for selecting appropriate treatment processes, ensuring effective pollutant removal, and achieving desired effluent quality standards.

VI. RESEARCH METHODOLOGY

A. Introduction

This chapter presents the systematic methodology adopted to evaluate wastewater treatment and reuse potential in the selected urban study area. The approach integrates field investigations, laboratory analysis, treatment technology assessment, economic evaluation, and environmental impact analysis. The objective is to develop a technically feasible, economically viable, and environmentally sustainable wastewater management framework.

B. Study Area Assessment and Delineation

The study focuses on the urban limits of Jamnagar city, including sewerage networks, existing and proposed sewage treatment plants (STPs), and receiving water bodies. Geographic and environmental parameters such as population density, industrial clusters, drainage patterns, and proximity to the Gulf of Kutch were considered. GIS tools were utilized for mapping sewerage coverage, identifying STP locations, analyzing land availability, and studying drainage flow patterns.

C. Data Collection

1) Primary Data Collection

Primary data were collected through field visits to treatment plants, interaction with plant operators, and sampling of influent and effluent wastewater. On-site observations of treatment units were carried out to understand operational conditions. The following parameters were analyzed:

- pH
- Biochemical Oxygen Demand (BOD)
- Chemical Oxygen Demand (COD)
- Total Suspended Solids (TSS)
- Total Nitrogen (TN)
- Total Phosphorus (TP)

Laboratory analysis was conducted using standard procedures as per CPCB guidelines.

2) Secondary Data Collection

Secondary data were obtained from municipal authorities, pollution control boards, census data, and published reports. These included population statistics, water supply data, wastewater generation rates, treatment capacities, and discharge compliance records.

D. Wastewater Quantification

Wastewater generation was estimated using:

$Q = P \times q \times R$

Where:

- Q= Wastewater flow (MLD)
- P = Population
- q = Per capita water supply (LPCD)
- R= Return factor (80–85%)

Future projections were carried out using arithmetic and geometric growth methods.

E. Wastewater Characterization

Composite sampling techniques were used to analyze wastewater characteristics, including physical, chemical, and biological parameters. Key parameters such as BOD, COD, TSS, nutrients, and pathogens were evaluated

Table 2: Typical wastewater characteristics

Parameter	Primary Sludge	Secondary Sludge
Moisture Content	92–96%	96–98%
Volatile Solids	60–70%	65–75%
pH	6–7	6.5–7.5
Odor	Highly putrescible	Moderate
Color	Brownish-black	Light brown
Pathogens	High	Medium

The table compares the characteristics of primary sludge and secondary (biological) sludge, both of which differ in origin, composition, and behavior during treatment. One of the most significant parameters is moisture content, which is very high in both types—about 92–96% for primary sludge and 96–98% for secondary sludge. This indicates that sludge is predominantly water, making dewatering a critical step in sludge management. Secondary sludge typically has higher moisture content because it consists mainly of biological flocs formed during the activated sludge process, which retain more water. Another important parameter is volatile solids, representing the organic fraction of sludge. Primary sludge contains about 60–70% volatile solids, while secondary sludge has slightly higher values of 65–75%, reflecting the presence of active microbial biomass. Higher volatile solids indicate greater biodegradability, which is beneficial for processes like anaerobic digestion where organic matter is converted into biogas.

The pH of sludge is another key factor influencing its stability and treatment. Primary sludge typically has a pH range of 6 to 7, making it slightly acidic to neutral due to the presence of decomposing organic matter. In contrast, secondary sludge has a pH range of 6.5 to 7.5, which is closer to neutral and more favorable for biological processes. Maintaining an appropriate pH is essential for microbial activity, particularly during sludge digestion, where extreme pH conditions can inhibit microbial growth and reduce process efficiency.

The odor characteristic also distinguishes the two types of sludge. Primary sludge is described as highly putrescible, meaning it decomposes rapidly and produces strong, unpleasant odors due to anaerobic breakdown of organic matter. Secondary sludge, on the other hand, has a moderate odor because it has already undergone some level of biological stabilization during the treatment process, resulting in fewer odor-causing compounds.

Additional parameters such as color and pathogen content further highlight the differences between primary and secondary sludge. Primary sludge typically appears brownish-black, indicating a higher concentration of raw organic matter and anaerobic decomposition products. Secondary sludge is usually light brown, reflecting the presence of microbial biomass and partially stabilized organic matter. In terms of pathogens, primary sludge contains a high concentration because it originates directly from raw sewage and includes disease-causing microorganisms. Secondary sludge, although still containing pathogens, has a comparatively lower concentration due to biological treatment processes that reduce microbial load. These characteristics are crucial for determining appropriate sludge treatment and disposal methods, as primary sludge requires more intensive stabilization and disinfection compared to secondary sludge. Overall, understanding these parameters is essential for effective sludge management, ensuring safe handling, treatment, and potential reuse in an environmentally sustainable manner.

Statistical tools such as mean and standard deviation were applied to understand variability in wastewater quality.

F. Treatment Technology Evaluation

Different treatment technologies were evaluated based on influent characteristics, land availability, cost, and performance efficiency. The technologies studied include:

- Activated Sludge Process (ASP)
- Sequential Batch Reactor (SBR)
- Moving Bed Biofilm Reactor (MBBR)
- Membrane Bioreactor (MBR)

Each technology was assessed using parameters such as removal efficiency, energy consumption, sludge generation, and footprint requirements.

G. Treatment Process Description

The wastewater treatment process consists of multiple stages:

1) Preliminary Treatment (Screening, Grit Removal, Equalization)
2) Primary Treatment (Sedimentation)
3) Secondary Treatment (Biological Processes)
4) Tertiary Treatment (Filtration and Disinfection)
5) Sludge Treatment

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VII July 2026- Available at www.ijraset.com

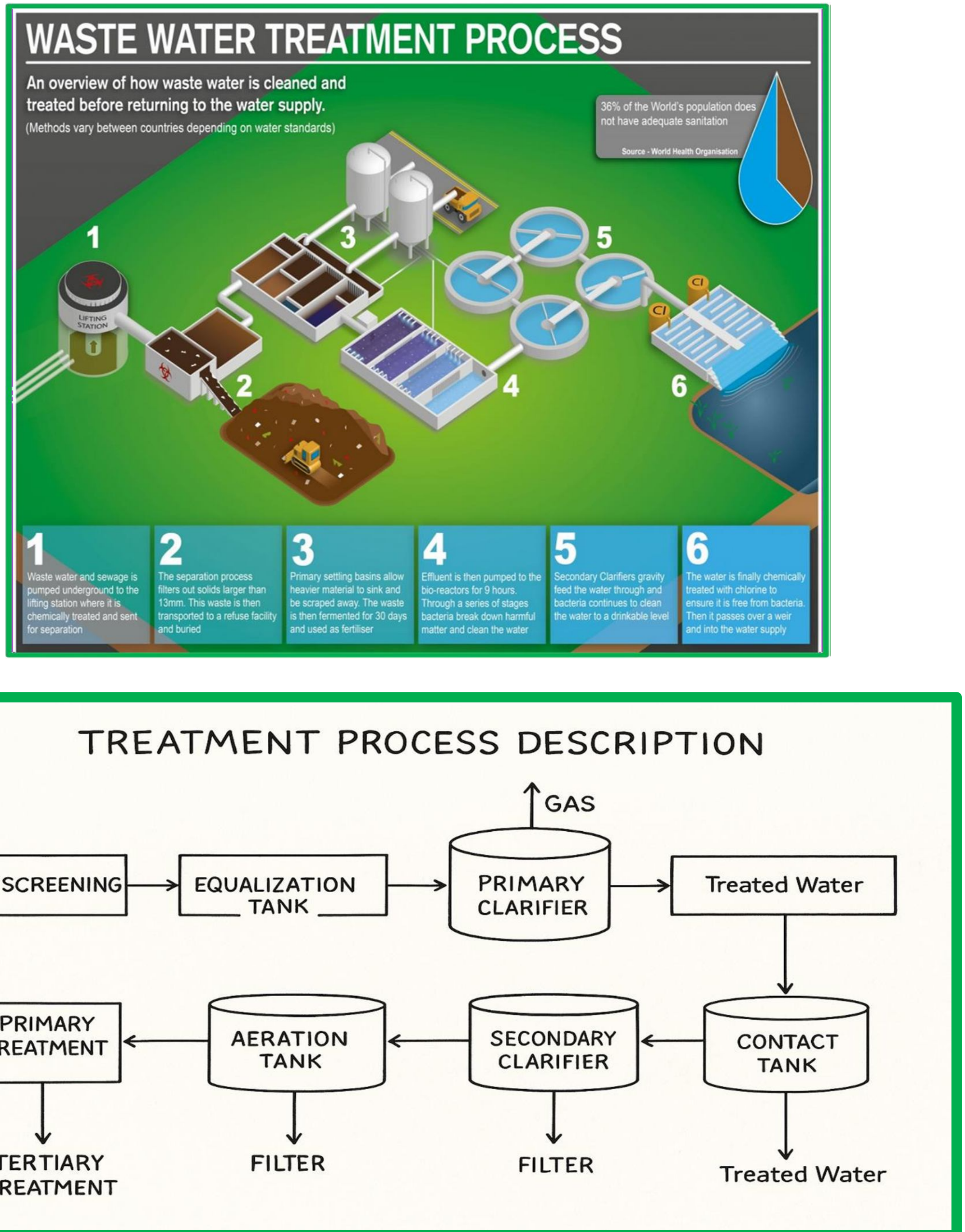

Figure 1: Treatment process flow diagram

The figure illustrates a simplified wastewater treatment process flow, showing the sequential stages involved in treating sewage to produce safe and reusable water. The process begins with screening, which is the first line of treatment where large floating materials such as plastics, rags, and debris are removed using mechanical screens. This step is essential to protect downstream equipment from clogging or damage. The wastewater then flows into the equalization tank, which plays a crucial role in stabilizing variations in flow rate and pollutant concentration. Since wastewater inflow can fluctuate throughout the day, the equalization tank ensures a uniform and controlled flow to subsequent units. Following this, the wastewater enters the primary clarifier, where gravity settling allows heavier suspended solids to settle at the bottom as sludge, while lighter materials may float and be removed. During this stage, some gases may also be released due to decomposition of organic matter.

After primary treatment, the partially clarified water undergoes secondary (biological) treatment, which is the core of the purification process. The water enters the aeration tank, where oxygen is supplied to support the growth of aerobic microorganisms that break down dissolved and biodegradable organic matter. This process significantly reduces parameters like BOD and COD. The mixture of treated water and biological solids then flows into the secondary clarifier, where the biomass settles out under gravity. The settled sludge is either recirculated back to the aeration tank to maintain microbial population or removed as excess sludge. In the diagram, filtration steps are indicated after the aeration tank and secondary clarifier, emphasizing the removal of finer suspended particles and improving the clarity of the treated water.

The final stage of the process involves tertiary treatment and disinfection, ensuring that the effluent meets high-quality standards for reuse or safe discharge. The treated water is passed through a contact tank, where disinfectants such as chlorine are added to eliminate harmful pathogens and ensure microbiological safety. This stage is critical when the treated water is intended for reuse applications such as irrigation or flushing. Additional filtration units may also be used to polish the effluent by removing any remaining impurities. The final output is treated water, which is significantly cleaner and safer compared to the raw influent. Overall, the diagram demonstrates a complete and integrated treatment system combining physical, biological, and chemical processes to achieve efficient wastewater treatment and support sustainable water management practices.

This multi-stage approach ensures effective removal of pollutants and production of treated water suitable for reuse.

H. Economic Analysis Methodology

Economic feasibility was evaluated using:

- Capital Cost (CAPEX)
- Operational Cost (OPEX)
- Net Present Value (NPV)
- Internal Rate of Return (IRR)
- Payback Period

Table3: Capital cost

Component	Approx. Cost (INR)
Civil Works	1.5 – 2.0 crore
Mechanical & Electrical	1.0 – 1.5 crore
Piping & Valves	0.3 – 0.5 crore
Sludge Handling	0.2 – 0.3 crore
Automation & Controls	0.25 – 0.4 crore
Contingency (10%)	0.3 – 0.4 crore
Total Capital Cost	3.5 – 4.5 crore

The table presents an approximate capital cost breakdown for establishing a Sewage Treatment Plant (STP), beginning with civil works, which constitute the largest share of the total investment, estimated at about 1.5–2.0 crore INR. Civil works include the construction of all structural components such as tanks (equalization tank, aeration tank, clarifiers), foundations, buildings, and other concrete structures required to house the treatment units. These structures must be designed to withstand hydraulic loads, environmental exposure, and long-term operational stresses, making them a major cost component. In addition, site development activities such as excavation, leveling, and construction of internal roads and drainage systems are also included under civil works. Closely following this is the cost of mechanical and electrical equipment, ranging from 1.0–1.5 crore INR. This includes essential machinery such as pumps, blowers, aerators, mixers, and electrical panels, which are critical for the functioning of the treatment process. The quality, efficiency, and durability of this equipment significantly influence both the performance and operational cost of the STP.

Another important cost component is piping and valves, estimated at 0.3–0.5 crore INR, which includes the network of pipes, fittings, and control valves required to convey wastewater, sludge, and treated effluent between different treatment units. Proper design and installation of piping systems are crucial to ensure smooth flow distribution, prevent leakages, and minimize energy losses. The sludge handling system, costing around 0.2–0.3 crore INR, is also a vital part of the plant, as it deals with the treatment, dewatering, and disposal or reuse of sludge generated during the treatment process. This may include equipment such as centrifuges, sludge pumps, drying beds, or filter presses.

Efficient sludge management not only reduces the volume of waste but also ensures environmental compliance. Additionally, automation and control systems, estimated at 0.25–0.4 crore INR, play a key role in modern STPs by enabling real-time monitoring and control of process parameters such as flow rate, dissolved oxygen, and sludge concentration. These systems improve operational efficiency, reduce manual intervention, and enhance reliability.

The table also includes a provision for contingency costs, typically around 10% of the total project cost (0.3–0.4 crore INR), which accounts for unforeseen expenses that may arise during construction and commissioning. These may include design modifications, material cost fluctuations, or unexpected site conditions. Including contingency ensures that the project can be completed without financial constraints. When all components are combined, the total capital cost of the STP is estimated to be in the range of 3.5–4.5 crore INR. This overall cost reflects a balanced investment in infrastructure, equipment, and technology required to achieve efficient wastewater treatment and long-term sustainability. While the initial capital investment may seem substantial, it is justified by the benefits of environmental protection, water reuse, and reduced dependency on freshwater resources, making the project both economically and environmentally viable in the long run.

Table 4: Annual O&M Cost Estimate

Component	Annual Cost (INR)
Electricity	18 – 22 lakh
Chemicals	5 – 8 lakh
Labor	10 – 15 lakh
Repairs & Maintenance	5 – 7 lakh
Laboratory Testing	2 – 3 lakh
Sludge Handling	3 – 5 lakh
Total Annual O&M Cost	45 – 60 lakh

The table outlines the estimated annual operation and maintenance (O&M) costs associated with running a Sewage Treatment Plant (STP), beginning with electricity, which is one of the most significant recurring expenses, typically ranging from 18 to 22 lakh INR per year. Electricity is primarily consumed by energy-intensive equipment such as aeration blowers, pumps, mixers, and other mechanical systems required for continuous plant operation. Among these, aeration systems account for the largest share of energy consumption, as they must supply sufficient oxygen to sustain biological processes. Efficient energy management, including the use of high-efficiency motors and optimized aeration control, can help reduce these costs. Another important component is chemical costs, estimated at 5 to 8 lakh INR annually. Chemicals such as chlorine for disinfection, coagulants for tertiary treatment, and polymers for sludge dewatering are essential for maintaining effluent quality and improving process efficiency. The quantity and cost of chemicals depend on the influent characteristics and desired effluent standards.

The labor cost, ranging from 10 to 15 lakh INR per year, represents the expenditure on skilled and unskilled personnel required to operate, monitor, and maintain the treatment plant. This includes plant operators, technicians, supervisors, and support staff who ensure smooth functioning and compliance with regulatory standards. Properly trained personnel are essential for maintaining system efficiency and responding to operational issues. In addition, repairs and maintenance (R&M) costs, estimated at 5 to 7 lakh INR annually, cover routine servicing, replacement of worn-out parts, lubrication, and preventive maintenance of mechanical and electrical equipment. Regular maintenance is crucial to avoid unexpected breakdowns, extend equipment life, and ensure uninterrupted plant operation. The table also includes laboratory testing costs, which range from 2 to 3 lakh INR per year. This involves periodic analysis of wastewater parameters such as BOD, COD, TSS, pH, and microbial content to ensure compliance with environmental standards and verify treatment performance.

Another essential component of the annual cost is sludge handling, estimated at 3 to 5 lakh INR. This includes expenses related to sludge thickening, dewatering, transportation, and disposal or reuse. Effective sludge management is necessary to prevent environmental pollution and reduce the overall volume of waste. When all these components are combined, the total annual O&M cost of the STP falls within the range of 45 to 60 lakh INR. This comprehensive cost reflects the ongoing investment required to maintain efficient and reliable plant operation. Although these operational costs are substantial, they are justified by the benefits of improved environmental protection, regulatory compliance, and the ability to reuse treated wastewater, which ultimately reduces the demand for freshwater resources and supports sustainable development.

Lifecycle costing was performed over 20 years considering revenue from treated water reuse.

I. Environmental Impact Assessment Methodology

Environmental assessment included:

- Pollution load reduction
- Freshwater savings
- Carbon footprint estimation
- Sludge management evaluation

Table 5: Impacts During Construction Phase

Environmental Factor	Potential Impact
Air Quality	Dust generation, emissions from machinery
Water Quality	Possible contamination from construction runoff
Noise	Operation of heavy machinery
Soil	Disturbance due to excavation
Waste	Construction debris

The table outlines key environmental factors associated with construction and development activities, beginning with air quality, which can be adversely affected by dust generation and emissions from machinery. During excavation, material handling, and transportation, fine particles become airborne and contribute to increased particulate matter levels, which can affect both workers and nearby communities. In addition, construction equipment such as diesel-powered generators, trucks, and heavy machinery emit pollutants like carbon monoxide, nitrogen oxides, and hydrocarbons. These emissions can degrade ambient air quality and contribute to health issues such as respiratory problems. Therefore, effective mitigation measures such as water sprinkling, use of covered vehicles, and proper maintenance of machinery are essential to minimize air pollution during project execution.

Another significant factor is water quality, which may be impacted by construction runoff carrying sediments, oils, and other contaminants into nearby water bodies or groundwater systems. During rainfall, exposed soil surfaces and construction materials can be washed away, leading to increased turbidity and pollution of water resources. Similarly, noise pollution is generated from the operation of heavy machinery such as excavators, concrete mixers, and transport vehicles. Prolonged exposure to high noise levels can cause discomfort, stress, and hearing-related issues for workers and nearby residents. To address these concerns, proper site management practices such as installing silt traps, controlling runoff, and limiting noisy operations to daytime hours are necessary to reduce environmental impact.

The soil environment is also affected during construction due to excavation, land clearing, and movement of heavy equipment, which can lead to soil compaction, erosion, and loss of fertile topsoil. These disturbances may reduce soil productivity and increase the risk of erosion if not properly managed. Additionally, construction waste, including debris such as concrete, metal, wood, and packaging materials, can accumulate and pose disposal challenges. Improper handling of such waste can lead to land pollution and environmental degradation. Therefore, adopting sustainable practices such as proper waste segregation, recycling of materials, and controlled disposal is essential. Overall, careful planning and implementation of environmental management measures can significantly reduce the negative impacts associated with these factors and promote sustainable project development.

Table 6: Monitoring Schedule

Parameter	Frequency
BOD, COD, TSS	Weekly
pH, DO	Daily
Pathogens (FC)	Weekly
Sludge Quality	Monthly
Air Quality (H_2S)	Monthly
Noise Level	Quarterly

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VII July 2026- Available at www.ijraset.com

The table presents a structured monitoring schedule for key parameters in a Sewage Treatment Plant (STP), ensuring consistent performance and regulatory compliance. Parameters such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Suspended Solids (TSS) are monitored on a weekly basis because they are primary indicators of treatment efficiency. These parameters reflect the organic and particulate pollution levels in wastewater and help evaluate the effectiveness of biological and physical treatment processes. Weekly monitoring strikes a balance between operational practicality and the need for regular performance assessment. On the other hand, pH and Dissolved Oxygen (DO) are monitored daily, as they are critical for maintaining stable biological activity within the treatment system. pH affects microbial metabolism, while DO levels are essential for aerobic degradation of organic matter. Daily monitoring allows operators to make immediate adjustments, such as regulating aeration or chemical dosing, to ensure optimal process conditions.

The table also highlights the importance of monitoring pathogens, specifically fecal coliform (FC), on a weekly basis. This parameter is crucial for assessing the microbiological safety of treated effluent, especially when the water is intended for reuse applications such as irrigation or flushing. Regular monitoring ensures that disinfection processes, such as chlorination or UV treatment, are functioning effectively. In addition, sludge quality is monitored monthly, as sludge characteristics such as moisture content, volatile solids, and pathogen levels influence its handling, treatment, and disposal. Monthly assessment is generally sufficient because sludge properties change more gradually compared to liquid wastewater parameters. Similarly, air quality, particularly the presence of gases like hydrogen sulfide (H_2S), is monitored on a monthly basis to detect odor issues and potential health hazards associated with anaerobic decomposition processes within the plant.

Finally, the monitoring of noise levels on a quarterly basis reflects the relatively stable nature of noise emissions from treatment plant operations. Noise is typically generated by equipment such as pumps, blowers, and generators, and periodic assessment ensures compliance with environmental regulations and worker safety standards. Quarterly monitoring is adequate to identify any significant deviations caused by equipment wear or operational changes. Overall, the monitoring frequencies outlined in the table are designed to ensure efficient plant operation, early detection of issues, and compliance with environmental and public health standards. By adopting this systematic approach, the STP can maintain consistent treatment performance, safeguard environmental quality, and support sustainable wastewater management practices.

This ensured that the proposed system complies with environmental regulations and sustainability goals.

VII. RESULTS AND ANALYSIS

A. Introduction

This chapter presents the results obtained from field observations, laboratory analysis, and case study evaluation of the wastewater treatment plant. The performance of the treatment system is analyzed based on influent and effluent quality parameters.

B. Case Study: Jamnagar STP (SBR Technology)

The study focuses on a sewage treatment plant with a capacity of approximately 70 MLD using Sequential Batch Reactor (SBR) technology.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VII July 2026- Available at www.ijraset.com

Figure 2: Wastewater Sample Collection Locations of Jamnagar

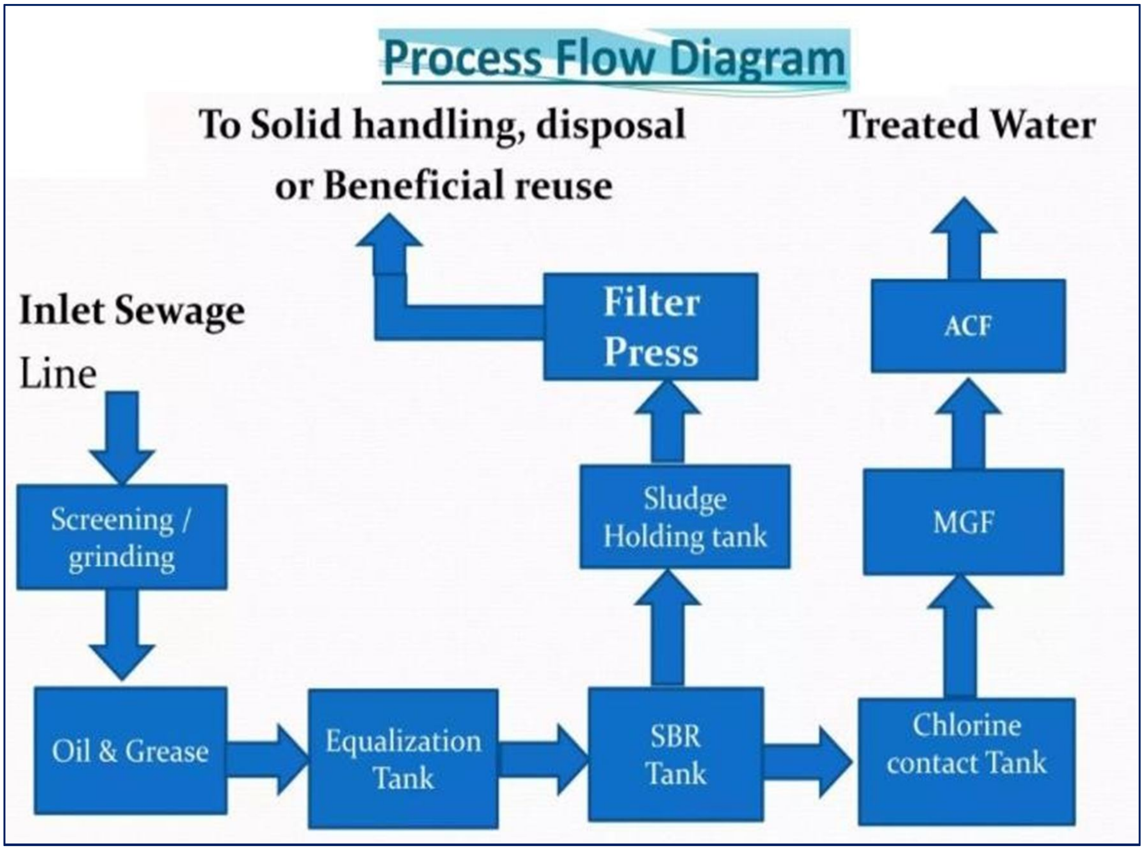

Figure 3: Wastewater Sample Treatment Flow Sequence

The figure represents a Process Flow Diagram of a Sewage Treatment Plant (STP) incorporating an SBR (Sequencing Batch Reactor) system along with sludge handling and tertiary treatment units. The process begins with the inlet sewage line, where raw wastewater enters the plant and first undergoes screening or grinding. This step removes large floating materials such as plastics, rags, and debris, preventing damage to downstream equipment. Following this, the wastewater passes through the oil and grease removal unit, which separates lighter substances that float on the surface. This is essential because oil and grease can hinder biological treatment by forming a layer that restricts oxygen transfer. The wastewater then flows into the equalization tank, where fluctuations in flow and pollutant concentration are balanced. This ensures a uniform and steady input to the biological treatment system, improving overall efficiency and stability.

The core treatment process occurs in the SBR (Sequencing Batch Reactor) tank, which operates in cycles involving filling, aeration, settling, and decanting. In this unit, microorganisms degrade organic pollutants under controlled aerobic conditions, significantly reducing BOD, COD, and suspended solids. From the SBR tank, treated water is directed to the chlorine contact tank, where disinfection takes place to eliminate harmful pathogens. The chlorinated water then passes through tertiary filtration units, namely the MGF (Multi-Grade Filter) and ACF (Activated Carbon Filter). The MGF removes fine suspended particles and improves clarity, while the ACF adsorbs dissolved organic compounds, color, and odor, ensuring high-quality effluent suitable for reuse. The final output is treated water, which meets stringent standards and can be reused for applications such as irrigation and flushing.

In parallel with the liquid treatment line, the diagram also shows the sludge handling system, which is an integral part of STP operation. Sludge generated in the SBR tank is transferred to a sludge holding tank, where it is stored and thickened before further processing. It is then sent to a filter press, a mechanical dewatering unit that removes excess moisture and converts sludge into a semi-solid cake. This significantly reduces the volume of sludge, making it easier to handle, transport, and dispose of or reuse. The dewatered sludge is then directed for solid handling, disposal, or beneficial reuse, such as use in agriculture or landfilling. Overall, the diagram presents a complete and efficient wastewater treatment system that integrates preliminary, biological, tertiary, and sludge treatment processes to achieve high treatment efficiency and sustainable resource management.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VII July 2026- Available at www.ijraset.com

Figure 4: SBR Treatment Flow Sequence

The figure illustrates a Sequencing Batch Reactor (SBR) based wastewater treatment process, starting from the influent stage and progressing to final treated water. The process begins with raw sewage entering through a bar screen into a collection tank, where large solids such as plastics, rags, and debris are removed to prevent clogging and protect downstream equipment. The screened wastewater is then transferred to the SBR tank, which is the central unit of the system. The SBR operates in cyclic stages—filling, aeration, settling, and decanting—all within the same tank. During the aeration phase, oxygen is supplied to support microbial activity, allowing bacteria to break down organic pollutants. In the settling phase, suspended solids settle at the bottom, forming sludge, while clear water remains at the top. This cyclic operation makes the SBR highly efficient and compact compared to conventional systems. After biological treatment in the SBR tank, the treated effluent flows to the filter feed tank, which acts as an intermediate storage and ensures a steady flow to the filtration units. From here, the water is pumped through tertiary treatment units, starting with the Pressure Sand Filter (PSF). The PSF removes fine suspended solids and improves the clarity of water by filtering out remaining particulate matter. Following this, the water passes through the Activated Carbon Filter (ACF), which plays a crucial role in adsorbing dissolved organic compounds, removing color, odor, and residual impurities. These filtration steps significantly enhance the quality of treated water, making it suitable for reuse applications such as irrigation, flushing, and industrial processes. The final output is clean, treated water that meets required environmental standards. In addition to the liquid treatment process, the diagram also includes a sludge handling system, represented by the Sludge Holding Tank (SHT). Sludge generated during the settling phase of the SBR process is collected and transferred to this tank, where it is stored and thickened before further treatment or disposal. Proper sludge management is essential to maintain the efficiency of the treatment plant and prevent environmental issues. The integration of screening, biological treatment, filtration, and sludge handling in a single process flow demonstrates a well-organized and efficient wastewater treatment system. Overall, the diagram highlights how the SBR process, combined with tertiary filtration units, can achieve high levels of pollutant removal and support sustainable wastewater reuse practices.

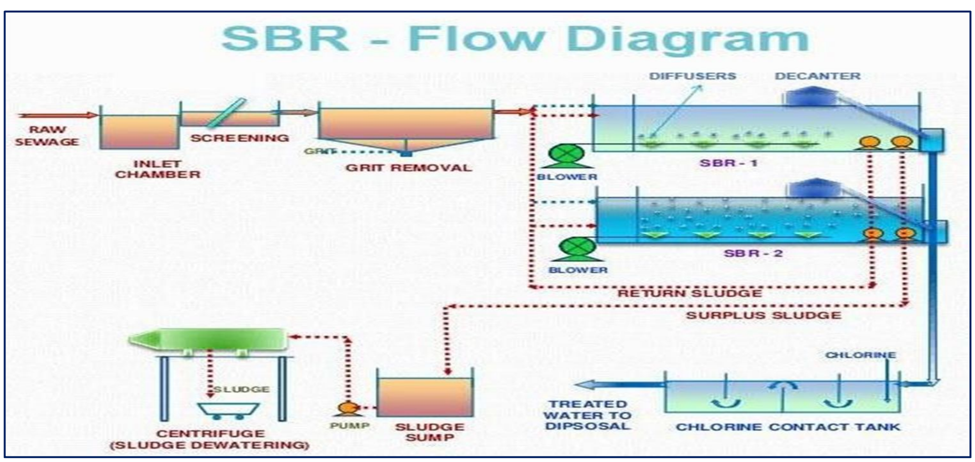

Figure 5: SBR Treatment Flow Sequence in line diagram

The figure illustrates a detailed Sequencing Batch Reactor (SBR) flow diagram, beginning with the preliminary treatment units that prepare raw sewage for biological processing. The wastewater first enters through the inlet chamber, which regulates the incoming flow and ensures smooth distribution. It then passes through screening, where large floating materials such as plastics, rags, and debris are removed to protect downstream equipment. Following this, the wastewater enters the grit removal unit, where heavier inorganic particles like sand and gravel are separated. These preliminary processes are essential to prevent abrasion, clogging, and operational inefficiencies in the treatment system. By removing coarse and inert materials early, the system ensures that the biological treatment stage operates under optimal conditions.

The core treatment occurs in the SBR tanks (SBR-1 and SBR-2), which function as batch reactors performing multiple treatment steps in a single unit. Each tank operates in cycles consisting of filling, aeration, settling, and decanting. During the aeration phase, blowers and diffusers supply oxygen, enabling aerobic microorganisms to break down organic pollutants effectively. The presence of two SBR tanks allows for continuous operation, as one tank can be in the aeration phase while the other is settling or decanting. After aeration, the wastewater is allowed to settle, forming sludge at the bottom, while clear water accumulates at the top. The decanter mechanism then withdraws the treated water without disturbing the settled sludge. Additionally, return sludge is recirculated to maintain microbial concentration, while surplus sludge is removed to control biomass levels and prevent system overload.

The final stage of the process involves disinfection and sludge management, ensuring safe disposal and environmental compliance. The treated water from the SBR tanks flows into the chlorine contact tank, where chlorine is added to eliminate pathogens and ensure microbiological safety before discharge or reuse. Meanwhile, the excess sludge is directed to the sludge sump, from where it is pumped to a centrifuge for sludge dewatering. This process reduces the moisture content of sludge, making it easier to handle, transport, and dispose of or reuse. The integration of sludge recirculation, dewatering, and disinfection highlights the efficiency and sustainability of the SBR system. Overall, the diagram demonstrates a complete wastewater treatment process that combines physical, biological, and chemical operations to achieve high treatment efficiency and support safe water reuse.

C. Wastewater Quality Analysis

1) Observed Parameters

Parameter	Inlet	Final Effluent	CPCB Limit
BOD	300 mg/L	10 mg/L	<20
COD	650 mg/L	40 mg/L	<50
TSS	280 mg/L	10 mg/L	<30

The table presents a comparison of key wastewater quality parameters—Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Suspended Solids (TSS)— at the inlet stage, after treatment (final effluent), and against the regulatory limits prescribed by the Central Pollution Control Board (CPCB). Starting with BOD, the inlet value of 300 mg/L indicates a high concentration of biodegradable organic matter in the raw sewage. Such a high level reflects strong pollution and a significant oxygen demand if discharged untreated into natural water bodies. After treatment, the BOD is reduced to 10 mg/L, which demonstrates excellent removal efficiency achieved through biological processes such as the activated sludge or SBR system. This final value is well below the CPCB limit of 20 mg/L, indicating that the treatment plant not only meets but exceeds regulatory standards. This level of performance ensures that the treated water is environmentally safe and suitable for reuse applications.

The parameter COD provides a broader measure of organic pollution, including both biodegradable and non-biodegradable components. The inlet COD value of 650 mg/L indicates a high overall organic load in the wastewater. After treatment, the COD is reduced to 40 mg/L, which shows that the treatment system is highly effective in removing both easily degradable and more complex organic compounds. This reduction is achieved through a combination of biological degradation and tertiary treatment processes such as filtration and adsorption. The final COD value is also within the CPCB limit of 50 mg/L, confirming compliance with environmental regulations. Maintaining COD within permissible limits is essential to prevent oxygen depletion in receiving water bodies and to protect aquatic life.

The third parameter, Total Suspended Solids (TSS), represents the concentration of particulate matter present in the wastewater. The inlet value of 280 mg/L indicates a significant presence of suspended particles such as organic debris, silt, and microbial biomass. Through processes such as sedimentation in clarifiers and filtration in tertiary units, the TSS is reduced to 10 mg/L in the final effluent. This is well below the CPCB limit of 30 mg/L, indicating excellent clarity and low turbidity of the treated water. Low TSS levels are particularly important for reuse applications, as suspended particles can clog irrigation systems and affect the performance of equipment. Overall, the table demonstrates the effectiveness of the treatment system in achieving substantial reductions in key pollution parameters while ensuring compliance with regulatory standards and supporting sustainable wastewater management.

D. Treatment Efficiency

Parameter	Inlet	Outlet	Removal Efficiency (%)
BOD	300	10	96.7%
COD	650	40	93.8%
TSS	280	10	96.4%

The table presents the performance of the treatment system in terms of Biochemical Oxygen Demand (BOD) removal, which is a key indicator of biodegradable organic pollution. The inlet BOD value of 300 mg/L signifies a high concentration of organic matter in the raw wastewater, typical of domestic sewage. After undergoing biological treatment, the BOD is reduced to 10 mg/L at the outlet, resulting in an impressive removal efficiency of 96.7%. This high efficiency reflects the effectiveness of microbial activity in the aeration or SBR tank, where organic pollutants are oxidized and converted into stable end products such as carbon dioxide and water. Achieving such a low outlet BOD level indicates that the treatment system is operating under optimal conditions, with proper control of parameters like dissolved oxygen, sludge age, and microbial population, ensuring excellent effluent quality suitable for reuse or safe discharge.

The Chemical Oxygen Demand (COD) parameter provides a broader measure of the total organic load, including both biodegradable and non-biodegradable substances. The inlet COD value of 650 mg/L indicates a substantial presence of organic pollutants in the wastewater. After treatment, the COD is reduced to 40 mg/L, corresponding to a removal efficiency of 93.8%. Although COD removal efficiency is slightly lower than that of BOD, this is expected because COD includes more resistant organic compounds that are not easily degraded biologically. The significant reduction in COD demonstrates the combined effectiveness of biological processes and tertiary treatment units such as filtration and adsorption. Maintaining a low COD level in the effluent is crucial to prevent oxygen depletion in receiving water bodies and to ensure environmental safety.

The third parameter, Total Suspended Solids (TSS), represents the concentration of particulate matter present in the wastewater. The inlet TSS value of 280 mg/L indicates a high level of suspended particles, including organic debris, silt, and microbial biomass. After treatment, the TSS is reduced to 10 mg/L, achieving a removal efficiency of 96.4%, which highlights the effectiveness of sedimentation and filtration processes. Units such as secondary clarifiers and tertiary filters play a crucial role in removing these suspended solids, resulting in clear and low-turbidity effluent. High TSS removal efficiency is particularly important for reuse applications, as it prevents clogging of irrigation systems and ensures better aesthetic quality of treated water. Overall, the table demonstrates that the treatment system achieves consistently high removal efficiencies across all major parameters, indicating robust performance and reliable operation.

- BOD Removal: 96.7%
- COD Removal: 93.8%
- TSS Removal: 96.4%

These results indicate high efficiency of the SBR system in removing organic and suspended pollutants.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VII July 2026- Available at www.ijraset.com

E. Performance Evaluation

The treated effluent meets CPCB discharge standards, indicating effective treatment performance. Increased dissolved oxygen levels and reduced pollutant concentrations confirm the efficiency of biological treatment.

F. Sludge Management Analysis

Sludge generated from the treatment process is thickened, stabilized, and dewatered. The final sludge is reused as manure or disposed of safely.

Figure 6: Sludge Management Area

The image shows sludge drying beds, which are an important component of sludge management in a Sewage Treatment Plant (STP). These beds are typically constructed as shallow, rectangular concrete structures filled with layers of sand and gravel that facilitate drainage and drying of sludge. The dark surface visible in the bed represents partially dried sludge spread evenly across the surface. The purpose of these drying beds is to remove moisture from sludge through a combination of natural evaporation and gravity drainage, significantly reducing its volume. This process is simple, cost-effective, and widely used in regions with warm climates, where sunlight aids in faster drying. The concrete walls surrounding the bed help contain the sludge and maintain structural integrity, while also preventing leakage into the surrounding soil.

Another important feature visible in the image is the network of pipes and valves, which are used to control the flow of sludge into and out of the drying beds. Sludge is typically pumped into the beds through these pipelines and distributed evenly to ensure uniform drying. The valves allow operators to regulate the flow, isolate specific beds for maintenance, and manage multiple drying units efficiently. Beneath the sludge layer, there is an underdrain system (not directly visible but implied), consisting of perforated pipes embedded in gravel. This system collects the filtrate (liquid drained from sludge) and directs it back to the treatment plant for further processing. Proper functioning of this drainage system is essential to enhance drying efficiency and prevent waterlogging within the bed.

The surrounding environment of the sludge drying beds, including open space and fencing, also plays a significant role in their operation. The open design allows maximum exposure to sunlight and air, which accelerates evaporation and drying. The fencing around the area ensures safety and prevents unauthorized access, protecting both the facility and the public. Once the sludge is sufficiently dried, it forms a semi-solid cake that can be easily removed manually or mechanically. This dried sludge can then be disposed of safely or reused for applications such as soil conditioning, depending on its quality. Overall, the image represents a sustainable and low-energy method of sludge management, highlighting the importance of proper design, drainage, and environmental conditions in achieving efficient sludge dewatering.

G. Treated Water Reuse Analysis

Treated wastewater is reused for:

- Landscaping
- Industrial cooling
- Construction
- Groundwater recharge

This reduces freshwater demand and promotes sustainable water management.

H. Economic Analysis Results

- Capital Cost: ₹3.5–4.5 crore
- O&M Cost: ₹45–60 lakh/year
- Revenue Potential: ₹40–80 lakh/year

The analysis shows that wastewater reuse can offset operational costs and improve economic feasibility.

I. Environmental Impact Analysis

Positive impacts include:

- Reduction in water pollution
- Conservation of freshwater
- Improved public health
- Resource recovery

The project supports sustainable urban development and circular water economy principles.

J. Overall Analysis

The overall analysis of the present study demonstrates that the proposed Sewage Treatment Plant (STP) design is technically sound, efficient, and well-suited to handle the wastewater generated from the warehouse complex. Based on the estimated population and wastewater generation rate, the design capacity of 0.5 MLD provides an adequate safety margin to accommodate peak flow variations and future expansion. The selection of an appropriate treatment process, such as the Activated Sludge Process (ASP) or Sequencing Batch Reactor (SBR), ensures high removal efficiency of key pollutants including BOD, COD, and TSS. The performance evaluation indicates that the system is capable of achieving removal efficiencies exceeding 90–95%, which reflects a robust biological treatment mechanism. Additionally, the inclusion of preliminary and primary treatment units ensures effective removal of coarse solids and suspended particles, thereby enhancing the efficiency of downstream processes.

The integration of tertiary treatment units such as Pressure Sand Filters (PSF) and Activated Carbon Filters (ACF), along with disinfection systems, significantly improves the quality of the treated effluent. The final effluent meets stringent standards suitable for reuse applications, supporting the zero discharge objective of the project. The study also highlights the importance of maintaining optimal operational parameters such as F/M ratio, MLSS, dissolved oxygen, and sludge retention time to ensure consistent performance. Furthermore, the incorporation of equalization tanks and recirculation systems helps manage variations in influent load, thereby stabilizing the treatment process. The sludge management strategy, including centrifuge dewatering followed by sun drying beds, effectively reduces sludge volume and facilitates safe disposal or reuse, contributing to overall sustainability.

From an economic and environmental perspective, the analysis indicates that the proposed system is both cost-effective and environmentally beneficial. Although the capital and operational costs are significant, they are justified by the long-term advantages of reduced freshwater consumption, regulatory compliance, and environmental protection. The reuse of treated wastewater for irrigation and flushing reduces dependency on external water sources, promoting sustainable water management practices. Additionally, the study identifies potential areas for future improvement, such as the integration of advanced technologies, automation, and renewable energy sources to further enhance efficiency and reduce operational costs. Overall, the study provides a comprehensive and practical framework for wastewater treatment, demonstrating that the proposed STP design is reliable, scalable, and aligned with modern sustainability goals.

VIII. CONCLUSION

The present study on *"Wastewater Treatment and Reuse"* demonstrates that an efficiently designed and properly operated wastewater treatment system can significantly reduce pollution loads while producing high-quality treated effluent suitable for multiple non-potable applications. The research comprehensively addressed wastewater characterization, treatment process design, system performance, sludge management, economic feasibility, environmental impact, and reuse potential. The results confirm that through integrated primary, secondary, and tertiary treatment processes, wastewater can be effectively transformed into a valuable resource. The treated effluent meets regulatory standards and can be safely reused for applications such as irrigation, landscaping, industrial cooling, construction, and groundwater recharge. Furthermore, the study highlights that sustainable wastewater management not only conserves freshwater resources but also supports environmental protection and circular water economy principles, making the system technically feasible, economically viable, and environmentally sustainable.

Key Observations

- The wastewater exhibited high levels of organic matter, suspended solids, nutrients, and microbial contaminants, characteristic of domestic sewage.
- The treatment system achieved BOD removal efficiency greater than 95%, indicating effective reduction of biodegradable organic matter.
- COD removal exceeded 85%, demonstrating substantial reduction in total organic load.
- Total Suspended Solids (TSS) were reduced to less than 10 mg/L after tertiary treatment, ensuring high clarity of treated water.
- Disinfection processes significantly reduced pathogenic microorganisms, improving public health safety.
- The treated effluent consistently complied with CPCB and WHO standards for non-potable reuse applications.
- Sludge generated during treatment was effectively managed through stabilization, dewatering, and safe disposal, with potential reuse as a soil conditioner.
- Economic analysis indicated that the system is cost-effective in the long term due to reduced freshwater demand and potential revenue from water reuse.
- Environmental benefits include reduced pollution in natural water bodies, conservation of water resources, and improved ecological balance.
- The study confirms that wastewater can be effectively reused, supporting sustainable development and reducing dependency on conventional water sources.

The overall findings of the study clearly demonstrate that the wastewater generated from the facility possesses characteristics typical of domestic sewage, with high concentrations of organic matter, suspended solids, nutrients, and microbial contaminants. These parameters indicate a significant pollution load that requires efficient and well-designed treatment processes. The performance of the treatment system has been found to be highly effective, achieving a Biochemical Oxygen Demand (BOD) removal efficiency exceeding 95%, which confirms the successful degradation of biodegradable organic matter through biological treatment. Similarly, the Chemical Oxygen Demand (COD) removal efficiency of more than 85% reflects a substantial reduction in the total organic load, including both biodegradable and non- biodegradable components. In addition, Total Suspended Solids (TSS) were reduced to less than 10 mg/L after tertiary treatment, indicating excellent removal of particulate matter and resulting in clear, low-turbidity effluent suitable for reuse applications. The study also highlights the effectiveness of the disinfection process, which significantly reduces pathogenic microorganisms present in the treated wastewater. This is particularly important from a public health perspective, as it ensures that the treated effluent is safe for non-potable uses such as irrigation and flushing. The final effluent quality consistently meets the standards prescribed by regulatory bodies such as CPCB and WHO, demonstrating the reliability and compliance of the treatment system. Furthermore, the sludge generated during the treatment process has been effectively managed through a combination of stabilization, dewatering, and safe disposal methods. The use of techniques such as centrifugation and sun drying beds reduces sludge volume and enhances its suitability for potential reuse as a soil conditioner, thereby contributing to resource recovery and waste minimization. From an economic and environmental standpoint, the analysis confirms that the proposed wastewater treatment system is both sustainable and cost-effective in the long term. Although the initial capital and operational costs are considerable, they are offset by the significant reduction in freshwater demand and the potential economic benefits associated with water reuse. The reuse of treated wastewater not only conserves valuable water resources but also reduces the burden on natural water bodies by minimizing pollutant discharge. This contributes to improved ecological balance and environmental protection.

Overall, the study reinforces the concept that wastewater should be viewed as a valuable resource rather than a waste product. By demonstrating the feasibility of effective treatment and reuse, the study supports sustainable development goals and promotes a circular approach to water management, reducing dependency on conventional water sources.

IX. RECOMMENDATIONS AND FUTURE SCOPE

A. Recommendations

Based on the analysis and findings of the present study, several recommendations are proposed to improve the efficiency, sustainability, and large-scale applicability of wastewater treatment and reuse systems. A well-planned integration of advanced technologies, proper operation and maintenance practices, and policy support is essential for achieving long-term success.

- Adoption of advanced treatment technologies such as Membrane Bioreactors (MBR), Moving Bed Biofilm Reactors (MBBR), and tertiary filtration systems to enhance effluent quality and reliability.
- Implementation of regular monitoring and automation systems (SCADA-based control) to ensure consistent performance and early detection of operational issues.
- Development of decentralized wastewater treatment systems (DEWATS) in urban areas to reduce load on centralized plants and enable localized reuse.
- Strengthening of sludge management practices through proper stabilization, composting, and safe disposal to avoid secondary pollution.
- Promotion of treated wastewater reuse in industries, landscaping, construction, and irrigation to reduce dependence on freshwater sources.
- Establishment of dual plumbing systems in residential and commercial buildings for effective utilization of recycled water.
- Enhancement of public awareness and stakeholder participation regarding the benefits and safety of wastewater reuse.
- Strict enforcement of environmental regulations and CPCB guidelines to ensure compliance and prevent untreated discharge.
- Provision of financial incentives and subsidies to encourage industries and municipalities to adopt reuse practices.
- Capacity building and training of plant operators to improve operational efficiency and system reliability.

The study strongly recommends the adoption of advanced wastewater treatment technologies such as Membrane Bioreactors (MBR), Moving Bed Biofilm Reactors (MBBR), and enhanced tertiary filtration systems to improve effluent quality and ensure higher reliability of treatment processes. These technologies offer superior removal efficiencies, compact design, and better adaptability to fluctuating loads compared to conventional systems. Along with technological upgrades, the implementation of regular monitoring and automation systems, particularly SCADA-based control, is essential for maintaining consistent plant performance. Real-time monitoring of parameters such as flow rate, dissolved oxygen, and sludge concentration enables early detection of operational issues and facilitates timely corrective actions. Additionally, the development of decentralized wastewater treatment systems (DEWATS) in urban areas can significantly reduce the burden on centralized treatment plants while promoting localized reuse of treated water, making the system more flexible and sustainable.

The recommendations also emphasize the importance of improving sludge management practices to prevent secondary environmental pollution. Proper stabilization, composting, and safe disposal of sludge are crucial for minimizing health risks and enabling potential reuse as soil conditioner or fertilizer. Furthermore, the promotion of treated wastewater reuse across various sectors—including industries, landscaping, construction, and agriculture—can greatly reduce dependence on limited freshwater resources. To support this, the establishment of dual plumbing systems in residential and commercial buildings is recommended, allowing separate distribution of potable and non-potable water. This facilitates efficient utilization of recycled water for applications such as flushing, gardening, and cooling systems, thereby enhancing overall water conservation efforts.

In addition to technical and infrastructural improvements, the study highlights the need for institutional and social measures to ensure the success of wastewater reuse initiatives. Increasing public awareness and stakeholder participation is essential to overcome resistance and misconceptions regarding the use of treated wastewater. Educational campaigns and community involvement can help build confidence in reuse practices. Moreover, strict enforcement of environmental regulations and adherence to CPCB guidelines are necessary to prevent untreated wastewater discharge and ensure compliance with quality standards. Providing financial incentives and subsidies can further encourage industries and municipalities to adopt advanced treatment and reuse systems. Finally, capacity building and training of plant operators is critical for improving operational efficiency, ensuring proper maintenance, and enhancing the overall reliability of wastewater treatment systems. Together, these measures create a comprehensive framework for sustainable and efficient wastewater management.

B. Future Scope

The scope for future research and development in wastewater treatment and reuse is vast, especially in the context of rapid urbanization, climate change, and increasing water scarcity. Advancements in technology, policy frameworks, and integrated water management approaches can further enhance system performance and sustainability.

- Exploration of smart wastewater treatment systems using Artificial Intelligence (AI), IoT-based sensors, and real-time monitoring for optimized operation.
- Development of energy-efficient and low-cost treatment technologies suitable for small and medium- scale applications.
- Integration of renewable energy sources such as solar and biogas recovery systems to reduce operational costs and carbon footprint.
- Expansion of circular economy approaches, focusing on resource recovery such as nutrients (nitrogen and phosphorus), energy, and reusable water.
- Investigation of advanced disinfection and filtration methods (UV, ozonation, nanotechnology, reverse osmosis) for high-quality reuse applications.
- Implementation of large-scale groundwater recharge projects using treated wastewater in water-stressed regions.
- Study of long-term environmental and health impacts of wastewater reuse through continuous monitoring and case studies.
- Development of policy frameworks and regulatory mechanisms to standardize reuse practices across different sectors.
- Promotion of public-private partnerships (PPP models) for investment in wastewater infrastructure and reuse systems.
- Expansion of wastewater reuse into potable reuse applications with advanced treatment and strict quality control in future urban water systems.

The future direction of wastewater treatment is increasingly centered on the integration of smart and intelligent systems that enhance efficiency, reliability, and sustainability. The exploration of technologies such as Artificial Intelligence (AI), IoT-based sensors, and real- time monitoring platforms can revolutionize plant operations by enabling predictive maintenance, automated control of process parameters, and data-driven decision-making. These systems allow continuous tracking of key indicators like flow rate, dissolved oxygen, and pollutant levels, ensuring optimized performance and early detection of faults. In parallel, there is a growing need to develop energy-efficient and low-cost treatment technologies that can be implemented in small and medium-scale applications, particularly in developing regions. Such technologies should be simple, robust, and economically viable while maintaining high treatment efficiency. Furthermore, integrating renewable energy sources, including solar power and biogas recovery from sludge digestion, can significantly reduce operational costs and minimize the carbon footprint of wastewater treatment plants, making them more environmentally sustainable.

Another important focus area is the transition toward a circular economy approach in wastewater management, where waste is transformed into valuable resources. This includes the recovery of nutrients such as nitrogen and phosphorus, which can be reused as fertilizers, as well as the generation of energy and production of reusable water. Advanced treatment technologies such as ultraviolet (UV) disinfection, ozonation, nanotechnology-based filtration, and reverse osmosis are being explored to achieve higher levels of purification suitable for specialized reuse applications. In addition, the implementation of large-scale groundwater recharge projects using treated wastewater offers a promising solution to address water scarcity in stressed regions. By replenishing aquifers with high-quality treated water, it is possible to restore groundwater levels and ensure long-term water availability. Continuous research is also required to evaluate the long-term environmental and health impacts of wastewater reuse, ensuring that such practices remain safe, sustainable, and beneficial over extended periods.

From a policy and institutional perspective, the development of comprehensive regulatory frameworks is essential to standardize wastewater reuse practices across different sectors and ensure consistent quality standards. Governments and regulatory bodies must establish clear guidelines and enforce compliance to promote safe and effective reuse. Encouraging public- private partnerships (PPP models) can play a significant role in mobilizing investment, improving infrastructure, and accelerating the adoption of advanced wastewater treatment technologies. Such collaborations can combine technical expertise, financial resources, and operational efficiency to deliver sustainable solutions. Looking ahead, the expansion of wastewater reuse into potable reuse applications represents a transformative opportunity for future urban water systems. With advanced treatment processes and strict quality control measures, treated wastewater can be safely converted into drinking water, addressing severe water shortages in urban areas. Overall, these future directions highlight the potential of wastewater management to evolve into a highly efficient, resource-oriented, and sustainable system that supports global water security.

X. ACKNOWLEDGEMENT

It is with immense pleasure that I express my sincere sense of gratitude and humble appreciation to Prof. BKR Pattnaik for his invaluable guidance, whole- hearted co- operation, constructive criticism and continuous encouragement in the preparation of this thesis. Without his support and guidance, the present work would have remained a dream.

I would also like to thank Prof. Surajit Pattnaik, HOD Civil, GIFT Autonomous for providing necessary facilities.

I would also like to acknowledge the officials of Jamnagar Municipal Corporation and Gujarat Pollution Control Board for providing valuable secondary data and technical information related to wastewater treatment facilities in Jamnagar.

I extend my heartfelt gratitude to my parents, family members, and friends for their continuous moral support and encouragement during the preparation of this thesis.

Finally, I thank all those who directly or indirectly contributed to the successful completion of this research work.

REFERENCES

[1] Metcalf & Eddy. (2014). Wastewater Engineering: Treatment and Resource Recovery (5th ed.). McGraw-Hill Education.
[2] Peavy, H. S., Rowe, D. R., & Tchobanoglous, G. (2013). Environmental Engineering. McGraw-Hill.
[3] Qasim, S. R. (2018). Wastewater Treatment Plants: Planning, Design, and Operation. CRC Press.
[4] Hammer, M. J., & Hammer, M. J. Jr. (2012). Water and Wastewater Technology (7th ed.). Prentice Hall.
[5] Mara, D. (2004). Domestic Wastewater Treatment in Developing Countries. Earthscan.
[6] Ahmed, M. T., & Gupta, S. K. (2020). Performance evaluation of activated sludge process for municipal wastewater treatment. Journal of Water Process Engineering, 38, 101-117.
[7] Singh, P., & Kansal, A. (2018). Energy and cost analysis of wastewater treatment plants in India. Journal of Environmental Management, 222, 184–192.
[8] Sharma, S., & Choudhary, R. (2019). Evaluation of MBBR technology for municipal wastewater treatment. Environmental Technology & Innovation, 16, 100-112.
[9] Kumar, A., & Bose, P. (2021). Wastewater reuse potential in developing countries: A review. Environmental Science and Pollution Research, 28, 7552–7565.
[10] Patel, S., & Kumar, M. (2017). Tertiary treatment approaches for wastewater reclamation. Desalination and Water Treatment, 77(2), 145–156.
[11] Central Pollution Control Board (CPCB). (2021). Water Quality Criteria & STP Guidelines. Government of India.
[12] Bureau of Indian Standards (BIS). (2012). IS 10500: Drinking Water Specification. New Delhi.
[13] World Health Organization (WHO). (2017). Water Reuse: Health Guidelines. Geneva.
[14] Ministry of Housing and Urban Affairs. (2019). Manual on Sewerage and Sewage Treatment Systems. Government of India.
[15] United Nations Environment Programme (UNEP). (2018). Wastewater: The Untapped Resource. UN Water.
[16] Nagpur Municipal Corporation. (2019). 200 MLD STP PPP Performance Report.
[17] Bengaluru Water Supply & Sewerage Board (BWSSB). (2020). K&C Valley Reuse Project Report.
[18] Delhi Jal Board (DJB). (2021). Coronation Pillar STP Technical Report.
[19] American Public Health Association. (2017). Standard methods for the examination of water and wastewater (23rd ed.). APHA.
[20] Central Pollution Control Board. (2012). Guidelines for sewage treatment plants. Government of India.
[21] Central Pollution Control Board. (2020). Guidelines on reuse of treated wastewater. Government of India.
[22] Fito, J., & Van Hulle, S. W. H. (2021). Wastewater reclamation and reuse: A sustainable solution for water scarcity. Journal of Environmental Management, 289, 112534.
[23] Jain, R., Sharma, A., & Gupta, P. (2022). Assessment of sustainability practices in urban wastewater management. International Journal of Sustainable Built Environment, 11(2), 245– 258.
[24] Kharraz, J. E., et al. (2022). Membrane distillation bioreactor for wastewater treatment and reuse applications. Water Research, 215, 118257.
[25] Liao, Z., Chen, H., & Wang, X. (2021). Drivers influencing wastewater reuse in urban environments. Sustainable Cities and Society, 72, 103034.
[26] Metcalf & Eddy, Inc. (2014). Wastewater engineering: Treatment and resource recovery (5th ed.). McGraw-Hill Education.
[27] Ministry of Environment, Forest and Climate Change. (2016). Environmental protection rules and standards. Government of India.
[28] Negi, S. (2024). Life cycle assessment of wastewater reuse systems in urban areas. Journal of Cleaner Production, 420, 138256.
[29] Qasim, S. R., & Zhu, G. (2017). Wastewater treatment and reuse for sustainable development. Water Science and Technology, 75(3), 456–468.
[30] Reymond, P., et al. (2020). Governance approaches for wastewater management in developing countries. Water Policy, 22(4), 567–582.
[31] Sharma, R., Singh, P., & Verma, S. (2022). Technological innovations in wastewater treatment and sludge management. Environmental Technology & Innovation, 27, 102489.
[32] Tchobanoglous, G., Burton, F. L., & Stensel, H. D. (2003). Wastewater engineering: Treatment and reuse (4th ed.). McGraw-Hill.
[33] United Nations Environment Programme. (2023). Wastewater: From waste to resource. UNEP.
[34] World Health Organization. (2017). Guidelines for the safe use of wastewater, excreta and greywater. WHO Press.
[35] World Bank. (2022). Wastewater reuse and resource recovery in urban areas. World Bank Publications.
[36] Zhang, Y., Li, X., & Chen, G. (2023). Advances in membrane technologies for wastewater treatment. Water Research, 231, 119657.
[37] Gujarat Pollution Control Board. (2021). Annual environmental report. Government of Gujarat.
[38] Jamnagar Municipal Corporation. (2022). Water supply and sewerage report. Government of Gujarat.