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Comparative Study of Conventional and Modern Sewage Treatment Technologies - A Review

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Abstract: Sewage treatment is a crucial component of environmental engineering, aimed at minimizing the adverse impact of wastewater on the environment and public health. Conventional sewage treatment processes, such as Activated Sludge Process (ASP) and Trickling Filters (TF), have been widely used for decades. However, modern technologies, including Membrane Bioreactors (MBR), Moving Bed Biofilm Reactors (MBBR), and Sequencing Batch Reactors (SBR), offer improved efficiency and reduced operational costs. This review article provides a comparative analysis of conventional and modern sewage treatment technologies based on efficiency, cost, energy consumption, and environmental impact.
Keywords: Sewage Treatment, Conventional Treatment, Modern Technologies, Wastewater Management, Environmental Impact

I. INTRODUCTION

Sewage treatment plays a vital role in maintaining water quality and preventing environmental pollution. Traditional treatment methods have been effective in treating wastewater, but advancements in technology have led to the development of modern treatment systems that offer improved efficiency and sustainability. This paper aims to review and compare conventional and modern sewage treatment methods, highlighting their advantages and limitations. Sewage treatment is an essential aspect of environmental management that ensures wastewater is effectively treated before being discharged into natural water bodies or reused for various purposes. With increasing urbanization, industrialization, and population growth, the amount of wastewater generated has significantly increased, necessitating efficient treatment technologies. Traditional sewage treatment methods, such as the Activated Sludge Process (ASP) and Trickling Filters (TF), have long been employed to treat wastewater by biological and physical means. These methods, although effective, often come with limitations such as high sludge production, energy consumption, and land requirements. In contrast, modern treatment technologies like Membrane Bioreactors (MBR), Moving Bed Biofilm Reactors (MBBR), and Sequencing Batch Reactors (SBR) have emerged as efficient and sustainable alternatives. These advanced techniques enhance treatment efficiency, reduce operational costs, and minimize environmental impact. The shift towards innovative treatment technologies is driven by the need for more sustainable, energy-efficient, and compact systems that can effectively handle increasing wastewater volumes while meeting stringent environmental regulations. This paper aims to provide a comprehensive review of conventional and modern sewage treatment technologies, analyzing their working principles, efficiency, cost implications, and environmental impact to determine the most suitable approaches for contemporary wastewater management.

II. LITERATURE REVIEW

A. Present Scenario of STPs in India

In comparison to India's daily production of 72,368 MLD (1 million litres), the installed capacity of STP was estimated to be 31,841 MLD (43.9%). 60% of the total installed sewage capacity of the nation is distributed among the five states and the Union Territory (UT) of Maharashtra, Gujarat, Uttar Pradesh, Delhi, and Karnataka. Arunachal Pradesh, Andaman and Nicobar Islands, Lakshadweep Islands, Manipur, Meghalaya, and Nagaland don't have any or very few sewage treatment facilities. When it comes to overall wastewater production, Chandigarh takes the top spot.

Diverse Urban Local Bodies (ULBs) in India have recently prioritised the reuse of treated sewage and started using it for industrial washing, horticultural irrigation, non-contact impoundments, and other purposes.

For example:

- The Punjab govt. announced the State Treated Wastewater Policy 2017 to promote the recycling and reuse of treated sewage for non-potable uses.

- The Indian Agricultural Research Institute, Karnal, examined sewage farming which led to the recommendation of an irrigation method for sewage-fed tree plantings.
- In large condominiums and high-rise apartment buildings in major cities (Delhi, Mumbai, Bengaluru, and Chennai) treated grey water is being used on a trial scale for toilet flushing.

In India, there were significant disparities in STP coverage between metropolitan cities, tier-II cities, and smaller towns and rural areas. Major cities typically had more advanced and extensive sewage treatment infrastructure, while smaller towns often faced challenges in providing adequate wastewater treatment. The Indian government had launched various initiatives, such as the Atal Mission for Rejuvenation and Urban Transformation (AMRUT) and the Swachh Bharat Mission (SBM), to promote sanitation and improve sewage infrastructure in towns and cities. These programs aimed to increase the coverage of sewage treatment facilities. Some Indian towns were beginning to explore wastewater reuse for non-potable purposes, such as irrigation, industrial processes, and landscaping, to address water scarcity issues. Clean water bodies contribute to the town's aesthetics, which can boost tourism and property values. Additionally, having a functional STP can help attract businesses and industries, as they require access to reliable wastewater treatment to operate legally and sustainably. The present scenario of Sewage Treatment Plants (STPs) in India reflects a complex mix of progress and persistent challenges amid the country's rapid urbanization and increasing wastewater generation. As per recent data from the Central Pollution Control Board (CPCB), India generates more than 62,000 million liters per day (MLD) of sewage, yet only about 40–45% of this volume is treated effectively through operational STPs, indicating a significant shortfall in treatment capacity. While metropolitan cities like Delhi, Mumbai, Chennai, and Bengaluru have installed multiple STPs employing both conventional and advanced technologies such as Moving Bed Biofilm Reactors (MBBR) and Membrane Bioreactors (MBR), many smaller towns and rapidly growing urban centers lag in infrastructure development. A substantial portion of sewage either remains untreated or is discharged after only partial treatment, contributing to severe pollution of major rivers and water bodies, notably the Ganga, Yamuna, and others. Operational inefficiencies remain a major concern, with many STPs facing problems like under-utilization due to lack of sewer connectivity, poor maintenance, inadequate power supply, and shortage of skilled personnel. Additionally, the high cost of advanced treatment technologies and limited financial resources pose barriers to widespread adoption, especially in tier-2 and tier-3 cities. The government, through initiatives such as the National Mission for Clean Ganga (NMCG), Atal Mission for Rejuvenation and Urban Transformation (AMRUT), and Swachh Bharat Mission (Urban), is actively promoting the augmentation and modernization of STPs, including decentralized wastewater treatment systems, to expand treatment coverage and improve effluent quality. Increasing emphasis is also placed on resource recovery from sewage, such as biogas generation, nutrient recovery, and treated water reuse for irrigation and industrial applications, which aligns with sustainable development goals.

B. STPs in India

Sewage Treatment Plants (STPs) in India play a crucial role in managing the rapidly growing volumes of municipal wastewater generated by the country's expanding urban population. India faces significant challenges in wastewater treatment, as studies and reports consistently reveal a large gap between the volume of sewage generated and the capacity of installed STPs, resulting in a substantial portion of untreated or partially treated sewage being discharged directly into rivers, lakes, and other water bodies. The Central Pollution Control Board (CPCB) data indicate that while urban India produces over 60,000 million liters per day (MLD) of sewage, only about 37–40% of this is treated through operational STPs. Conventional technologies like activated sludge processes, oxidation ponds, and trickling filters dominate the STP landscape, although there has been a gradual shift towards incorporating modern biological treatment systems such as Moving Bed Biofilm Reactors (MBBR) and Membrane Bioreactors (MBR) in major metropolitan areas to meet stricter environmental norms. Despite these technological advances, many STPs in India struggle with operational inefficiencies, frequent breakdowns, insufficient maintenance, and inadequate skilled manpower, leading to suboptimal treatment performance and non-compliance with discharge standards. Additionally, factors like intermittent power supply, poor monitoring, and financial constraints further impede effective sewage treatment. Government initiatives, including the National Mission for Clean Ganga (NMCG), AMRUT (Atal Mission for Rejuvenation and Urban Transformation), and the Swachh Bharat Mission, have placed significant emphasis on improving sewage infrastructure, promoting decentralized wastewater treatment solutions, and integrating STPs into urban sanitation planning. Research studies highlight the growing adoption of decentralized STPs in smaller towns and peri-urban areas as a cost-effective and flexible approach to sewage management, especially where centralized sewer networks are absent or incomplete. Moreover, there is increasing recognition of the need to recover resources such as biogas, nutrients, and treated water from STPs, supporting circular economy concepts and reducing environmental pollution.

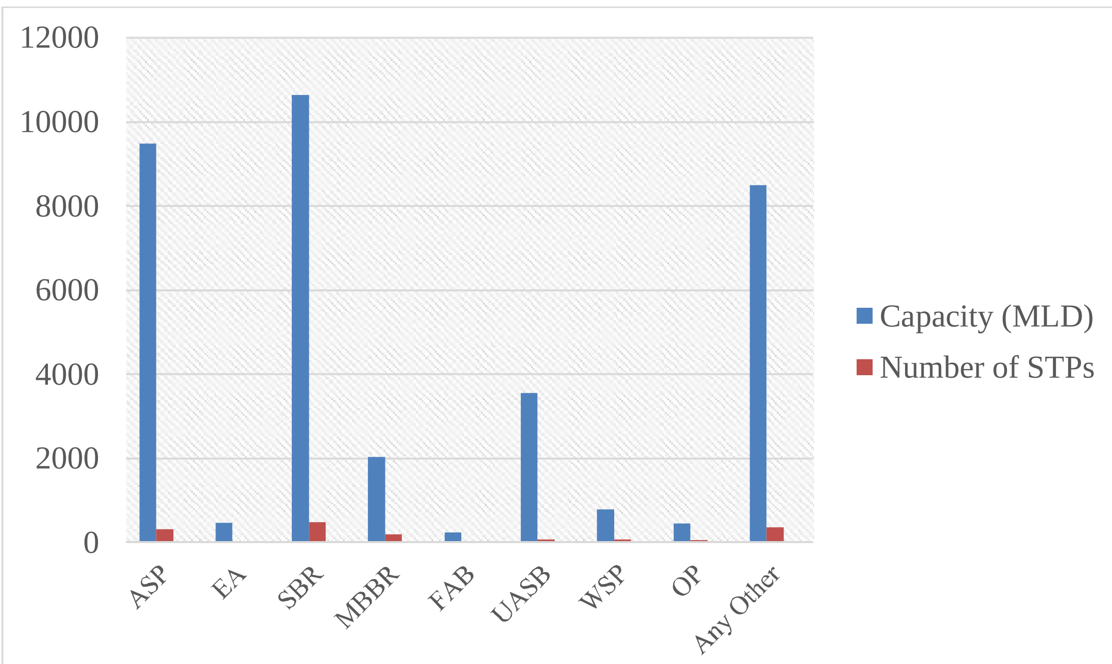
Challenges persist in terms of sludge management, with many plants lacking adequate facilities for sludge treatment and disposal, posing health and environmental risks. Policy frameworks and technological roadmaps are evolving to incorporate energy-efficient designs, automation, and real-time monitoring to enhance STP sustainability.

Overall, the literature and field data on STPs in India underscore a critical transition phase, with urgent requirements for capacity augmentation, modernization of treatment technologies, skilled workforce development, and robust regulatory enforcement to address the growing wastewater treatment demand and protect the country's precious water resources.Various technologies are employed in India for treatment of domestic wastewater. It is observed that Sequential Batch Reactor (SBR) and Activated Sludge Process (ASP) are the most prevailing technology adopted by ULBs.

Table 2.1: Technological distribution w.r.t number and capacity of STPs in India

SN	Technology	Capacity in MLD	Number of STPs
1.	Activated Sludge Process (ASP)	9486	321
2.	Extended Aeration Process (EA)	474	30
3.	Sequencing Batch Reactor (SBR)	10638	490
4.	Moving Bed Biofilm Reactor (MBBR)	2032	201
5.	Fluidised Aerobic Bio-Reactor (FAB)	242	21
6.	Upflow Anaerobic Sludge Blanket (UASB)	3562	76
7.	Waste Stabilization Ponds (WSP)	789	67
8.	Oxidation Pond (OP)	460	61
9.	Any Other	8497	364

Note: - Technologies included in Any Other are Aerated Lagoon (AL), Trickling Filter (TF), Bio-Tower, Electro Coagulation (EC), MBR, FMBR and Root Zone etc.

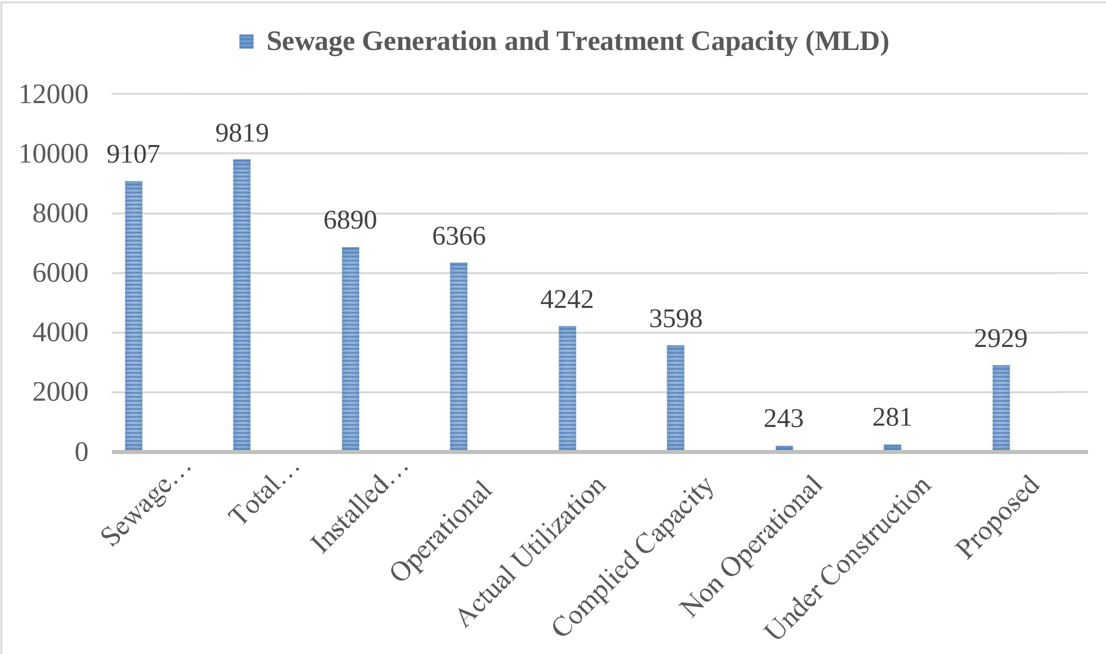


Graph 2.1: Number and capacity of different STPs technologies in India

C. STPs in Maharashtra

Maharashtra, with its large population and urban centres, generates a significant amount of sewage and wastewater. STPs are crucial to treating this sewage before it is discharged into rivers or bodies of water to prevent pollution and safeguard public health. The government of Maharashtra, in line with national policies and programs, has been focusing on improving wastewater management and sewage treatment. This includes initiatives to encourage the construction and operation of STPs and the adoption of sustainable and eco-friendly technologies. STPs must meet environmental compliance standards set by the Maharashtra Pollution Control Board (MPCB) and the Central Pollution Control Board (CPCB). Regular monitoring and reporting are required to ensure compliance with effluent quality norms.

Estimated sewage generation for the State of Maharashtra is 9,107 MLD and total capacity (including proposed) is 9,819 MLD (195 STPs). Many STPs in Maharashtra have undergone upgrades and expansion to cope with the increasing urbanization and population growth. These upgrades improve treatment efficiency and capacity. Local authorities, municipal corporations, and the Maharashtra Pollution Control Board (MPCB) play key roles in overseeing the planning, construction, and operation of STPs in the state.



Graph 2.2: Sewage Generation and Treatment Capacity (MLD) – Maharashtra

D. Review Of Existing Studies On Conventional STPS

Conventional Sewage Treatment Plants (STPs) have formed the backbone of municipal wastewater management for decades, and numerous studies have analyzed their design, performance, and limitations within various urban and rural contexts. Conventional STPs typically employ primary, secondary, and sometimes limited tertiary treatment processes, primarily focusing on physical settling, biological degradation through activated sludge or trickling filters, and basic disinfection methods. Existing research extensively documents the efficiency of these traditional treatment units in removing organic matter, suspended solids, and pathogens, though often with moderate effectiveness against nutrients such as nitrogen and phosphorus. Studies show that the primary sedimentation stage significantly reduces settleable solids and floating materials but is insufficient to meet stringent discharge standards without further biological treatment. The secondary treatment, predominantly using the Activated Sludge Process (ASP), has been widely studied and established as a robust, cost-effective technology capable of degrading biodegradable organic pollutants and reducing biochemical oxygen demand (BOD) to acceptable levels. However, literature also points out operational challenges like sludge bulking, aeration inefficiency, and sensitivity to toxic shocks that can affect treatment stability and effluent quality. Trickling filters and oxidation ponds, though less common in modern large-scale applications, remain relevant in low-cost and small-scale conventional STPs, particularly in developing regions, offering simple maintenance and low energy demands but often requiring larger land areas and longer retention times. Numerous researchers have critically evaluated the limitations of conventional STPs, highlighting inadequate nutrient removal as a major environmental concern leading to eutrophication in receiving water bodies. The absence of advanced nutrient removal stages in conventional setups necessitates the use of chemical precipitation or enhanced biological nutrient removal, which have been only partially incorporated in conventional frameworks. Studies on sludge management reveal that conventional STPs generate substantial quantities of primary and secondary sludge, requiring further treatment such as anaerobic digestion or dewatering to mitigate disposal issues, yet many facilities face challenges due to insufficient infrastructure and lack of sludge valorization. Moreover, conventional STPs generally rely on high energy inputs for aeration and pumping, which has been critically assessed in the literature concerning the increasing emphasis on sustainability and energy efficiency. Several studies recommend retrofitting and upgrading conventional STPs with modern technologies to improve overall performance, reduce footprint, and minimize environmental impact.

Despite their limitations, conventional STPs remain widely implemented due to their relatively straightforward design, ease of operation, and lower capital costs compared to advanced treatment technologies. Longitudinal performance assessments indicate that while conventional STPs can meet local discharge standards under optimal conditions, their effluent quality often falls short in addressing emerging contaminants, micropollutants, and stringent regulatory requirements. This gap in treatment capacity has spurred research into hybridizing conventional processes with newer treatment stages, such as biofilm reactors and membrane technologies, aiming to combine reliability with enhanced treatment efficacy. In summary, the body of existing literature on conventional STPs underscores their critical historical and ongoing role in wastewater management while identifying clear areas for technological improvement and sustainable operational strategies to meet future water quality and environmental protection goals.

Akshay Kshetre et al. (2018), "Comparative Study on Activated Sludge Process and Stabilization Pond to Reduce BOD", [1] emphasized the need for wastewater treatment and explored various available techniques. These included Activated Sludge Process (ASP), Trickling Filter, Extended Aeration Sludge Process, Aerated Lagoon, Oxidation Ditch, Waste Stabilization Pond (WSP), Up-flow Anaerobic Sludge Blanket (UASB), Membrane Bio-Reactor (MBR), Moving Bed Bio-Film Reactor (MBBR), Sequential Batch Reactor (SBR), and Rotating Biological Contactors (RBCs). Among these, the study particularly focused on a comparative analysis of the Activated Sludge Process and the Stabilization Pond in their effectiveness at reducing Biochemical Oxygen Demand (BOD). According to Kshetre et al. (2018), ASP is a widely used aerobic treatment process that offers a higher removal efficiency in a relatively compact space and within a shorter retention time. However, it requires skilled operation and higher energy input. On the other hand, Stabilization Ponds, while requiring a larger area and longer retention time, offer a more natural and cost-effective method for treating wastewater with minimal energy use and simpler operation. Their findings revealed that both methods are effective in BOD removal, but the choice between them largely depends on site-specific conditions, availability of land, and operational capabilities. The study serves as a valuable reference for selecting an appropriate biological treatment method based on environmental and economic considerations.

Rishabh Shukla et. al. (2022), “Performance evaluation and microbial community structure of a modified trickling filter and conventional activated sludge process in treating urban sewage”, [2] The performance and microbial community structure of a Modified Trickling Filter (MTF) and a conventional Activated Sludge Process (ASP) were analyzed in the context of urban sewage treatment. The MTF system, operated with a hydraulic retention time (HRT) of 2 hours and effluent recycling, was found to outperform the ASP system, which had an HRT of 8 hours, particularly in terms of nitrogen removal. Both systems achieved over 60% removal efficiency for chemical oxygen demand (COD), ammonia-nitrogen (NH_3-N), and phosphate (PO_4^{3-}-P); however, MTF demonstrated superior denitrification capability, with less than 5 mg/L of nitrate-nitrogen (NO_3^--N) detected in its effluent. A key highlight of the study was the higher abundance of nitrogen-removal functional genes such as amoA, nirK, nirS, napA, narG, and nosZ in the MTF system, indicating the dominance of simultaneous nitrification and denitrification (SND) processes. Using Miseq sequencing, the microbial communities in both systems were characterized, revealing a dominance of Proteobacteria, Planctomycetes, Chloroflexi, and Actinobacteriota. Notably, the co-occurrence of nitrifiers, denitrifiers, aerobic denitrifiers, and anaerobic ammonium oxidation (ANAMMOX) bacteria in the MTF suggested a more diverse and functionally active microbial ecosystem contributing to its enhanced nitrogen removal. The findings of Shukla and Ahammad (2022) underscore the potential of MTF as an efficient alternative to conventional ASP systems, especially in scenarios requiring compact design and effective nutrient removal.

Vikas Surve et. al. (2022), “Performance Evaluation of Oxidation Pond for Municipal Wastewater Treatment”, [3] Focused on the treatment plant located in Nandurbar city, Maharashtra. The research emphasized that despite the existence of a functioning sewage treatment plant (STP), irregular operation and poor maintenance significantly affected the plant's performance. To address this issue, oxidation ponds were proposed and evaluated for their suitability in treating wastewater efficiently. The study detailed the design of oxidation ponds meant to handle 2.0 MLD of wastewater, serving a population of approximately 111,174. The authors adopted a design temperature of 20°C and constructed five pond units with dimensions of 126.49 m × 63.24 m × 1.50 m. The oxidation pond system was categorized into anaerobic, facultative, and maturation ponds with respective depths of 1.5 m, 2.0 m, and 3.5 m. Based on a detention time of 30 days and a volume of 60,000 m³, the design accounted for BOD loading rate as the key parameter influenced by temperature. Weekly grab samples were collected from the outlet of the existing treatment plant, and chemical analyses were conducted to determine the removal efficiency of key parameters such as BOD, COD, TSS, and pH. A total of 40 tests showed significant reductions, with BOD and COD removal efficiencies ranging from 80% to 85%, thus indicating the oxidation pond’s potential in achieving effluent quality within permissible limits. The study concluded that oxidation ponds are an economical and effective option for tertiary treatment, particularly where space is not a constraint and agricultural reuse of treated wastewater is desired.

Priyanka Jamwal et. al. (2010), "Reuse of treated sewage in Delhi city: Microbial evaluation of STPs and reuse options", [4] Investigated the microbial quality of treated sewage in Delhi, with a specific focus on the evaluation of effluent from 16 different Sewage Treatment Plants (STPs) employing various treatment technologies including conventional Activated Sludge Process (ASP), extended aeration, BIOFORE (a combination of physical, chemical, and biological treatments), trickling filters, and oxidation ponds. The study emphasized the significance of Fecal Coliform (FC) and Fecal Streptococcus (FS) concentrations as critical parameters for determining the suitability of treated effluent for reuse purposes. Results indicated that extended hydraulic retention time (HRT), often caused by reduced influent flow, enhanced turbidity and contributed significantly to the removal of COD and BOD_5. ASP-based STPs showed an average removal of 1.66 log units of FC and 1.06 log units of FS, while those employing extended aeration achieved up to 4 log unit reductions in both microbial indicators, indicating superior treatment performance. Notably, the STPs at Kondli and Nilothi, despite using ASP, delivered higher quality secondary effluents than similar facilities. Furthermore, oxidation pond systems demonstrated effective microbial removal, although their overall physicochemical performance was more pronounced in the earlier stages of treatment. The researchers introduced the concept of actual integrated efficiency (IEa) to quantify the physical, chemical, and microbiological removal capabilities of each STP, thereby assessing their potential for reuse applications. While most STPs required tertiary treatment to meet reuse standards, especially for applications such as aquaculture, irrigation, and industrial water use, oxidation ponds and Mehrauli STP were considered inadequate without further treatment. This study provides crucial insights into tailoring reuse strategies based on treatment efficiency, location-specific factors, and potential end-uses of reclaimed wastewater.

Ashok Pandit et. al. (2013), "Current Research Trends in Wastewater Treatment-A Review", [5] Provide an extensive review of the evolving research trends in wastewater treatment, highlighting the complexity and diversity of approaches in managing sewage treatment processes. The authors emphasize the challenges in compiling comprehensive information due to the vast and scattered nature of research across various wastewater treatment methods. Their review synthesizes current developments in primary and secondary treatment technologies, focusing on critical indicators such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and trace metals as markers of treatment efficiency and environmental safety. The study underlines the importance of integrated treatment systems that combine physical, chemical, and biological processes to achieve enhanced pollutant removal. Moreover, they address the significance of monitoring trace metals and microbial indicators as essential parameters for assessing wastewater quality and treatment performance. The paper also highlights the emerging trends toward sustainable and eco-friendly wastewater management solutions, encouraging future research in optimizing treatment plant operations and improving effluent reuse potential. This review serves as a valuable resource by consolidating fragmented research findings, thereby providing a clearer understanding of contemporary wastewater treatment challenges and innovations.

E. Review of Existing Studies on Modern STPs

The evolution of modern Sewage Treatment Plants (STPs) has been extensively documented and analyzed across numerous studies, reflecting significant advancements in technology, process efficiency, environmental sustainability, and operational management. Modern STPs have shifted from traditional primary and secondary treatment processes to incorporating innovative tertiary and quaternary treatment technologies aimed at achieving higher pollutant removal efficiencies and enabling water reuse. Research emphasizes the integration of biological treatment methods such as Moving Bed Biofilm Reactors (MBBR), Membrane Bioreactors (MBR), and Sequencing Batch Reactors (SBR), which have been widely recognized for their compact design, enhanced treatment capabilities, and resilience against fluctuating influent loads. Studies by various authors highlight the superior nutrient removal performance of MBR systems, combining membrane filtration with activated sludge processes to achieve near-complete removal of suspended solids and pathogens, while reducing sludge production. Comparatively, MBBR technology has gained attention for its lower operational complexity and robustness, utilizing biofilm carriers to increase biomass concentration and improve organic matter degradation. Additionally, the integration of advanced oxidation processes (AOPs), ultraviolet (UV) disinfection, and nanofiltration within modern STPs has been shown to effectively reduce emerging contaminants, pharmaceutical residues, and microplastics, addressing the challenges posed by conventional treatment limitations. Several researchers have also focused on the use of constructed wetlands and phytorid systems as eco-friendly tertiary treatment options, promoting natural degradation processes with minimal energy input and maintenance costs, thus aligning with sustainable wastewater management principles. Furthermore, the optimization of STP design parameters, such as hydraulic retention time, aeration efficiency, and sludge management, has been a major focus to enhance energy efficiency and reduce greenhouse gas emissions associated with treatment operations.

In recent years, studies have explored the integration of smart monitoring systems and automation technologies, leveraging sensors, IoT, and machine learning algorithms to enable real-time process control, predictive maintenance, and operational cost savings. Life cycle assessment (LCA) and cost-benefit analyses in the literature underline the trade-offs between capital investment, operational expenses, and environmental impact, guiding policymakers and engineers toward selecting context-appropriate technologies for urban and rural wastewater treatment. Case studies from different geographical regions illustrate that decentralized STPs and modular designs are increasingly favored for their flexibility and scalability in rapidly urbanizing and resource-constrained settings. Moreover, the role of STPs in circular economy models is gaining traction, with research demonstrating the recovery of valuable resources such as biogas, nutrients (nitrogen and phosphorus), and treated water for irrigation and industrial reuse, thereby reducing environmental pollution and enhancing resource efficiency. Despite the remarkable progress, existing studies also identify challenges such as fouling in membrane systems, high energy demands of advanced treatments, and the need for skilled manpower, emphasizing continuous innovation and capacity building. Overall, the comprehensive review of existing literature on modern STPs underscores a transformative trajectory driven by technological innovation, environmental imperatives, and socio-economic factors aimed at achieving sustainable urban water management and safeguarding public health.

Anubhav Sharma et al. (2023) “A Review Paper on the Performance Evaluation of STPs Based on Different Technologies ASP, SBR & MBBR”, [1] have extensively discussed and evaluated the comparative performance of sewage treatment plants (STPs) operating on three major biological treatment technologies: Activated Sludge Process (ASP), Sequencing Batch Reactor (SBR), and Moving Bed Biofilm Reactor (MBBR). The authors began by emphasizing the critical importance of efficient and sustainable wastewater treatment systems in the face of rapidly increasing urbanization and pollution loads, highlighting the essential role played by STPs in ensuring environmental protection and public health. They reviewed various research studies and experimental findings that investigated key performance indicators such as removal efficiency of pollutants like BOD, COD, TSS, ammonia, nitrates, and phosphates, along with economic parameters including operating cost, energy requirement, and operational complexity. Sharma et al. (2023) found that while ASP remains one of the most widely adopted traditional biological treatment methods, it has certain limitations, particularly in terms of energy usage and space requirement. In contrast, SBR technology offers the advantage of combining equalization, aeration, and sedimentation in a single tank, which not only reduces footprint but also enhances process control, although it can be operationally intensive. Meanwhile, the MBBR system, which utilizes biofilm carriers suspended in the aeration tank, emerged as a more efficient and modern technology, with higher resilience to load fluctuations, superior nutrient removal capabilities, and lower sludge production. The review further observed that among the three, MBBR demonstrated superior adaptability, lower energy consumption per unit of treatment, and consistently higher removal efficiencies under various loading conditions, making it a promising candidate for future STP upgrades. Moreover, Sharma et al. (2023) underscored the significance of continuous monitoring, real-time data acquisition, and periodic performance evaluation of treatment plants to ensure compliance with effluent discharge standards as per regulatory norms. The paper also called for integrating innovative improvements such as automation, hybrid treatment combinations, and the use of advanced sensors and data analytics to further enhance the operational reliability and sustainability of these technologies. In conclusion, the study provided critical insights into the comparative merits and limitations of ASP, SBR, and MBBR systems, contributing to the decision-making framework for selecting appropriate treatment technologies in diverse geographical and economic contexts while considering long-term efficiency, scalability, and environmental impact.

Harpreet Kaur et. al. (2022), "A Comparative Study of Different Sewage Treatment Technologies", [2] emphasized the urgent necessity of adopting advanced and effective sewage treatment technologies that are not only technically sound but also environmentally sustainable. The authors highlighted how the traditional and conventional wastewater treatment systems are increasingly becoming inadequate in the face of rapidly growing urban populations and escalating pollution loads. These outdated systems, while once effective, now often suffer from high energy consumption, frequent operational failures, and space constraints—especially in densely populated urban areas where land availability is severely limited and infrastructure is overstressed. The paper underlines the importance of developing wastewater treatment strategies that not only focus on treating wastewater efficiently but also align with global and national sustainability goals, including those championed by bodies like the National Green Tribunal (NGT), which has taken a proactive stance on monitoring and improving the quality of rivers and other water bodies in India. Kaur and Sharma (2022) conducted a detailed comparative analysis of various modern sewage treatment technologies and advocated for a shift towards the Sequencing Batch Reactor (SBR) technology due to its operational advantages and high treatment performance. Through their study, it was found that SBR-based sewage treatment plants exhibit high removal efficiency for critical pollutants including Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Suspended Solids (SS), Ammonia Nitrogen (N), Total Kjeldahl Nitrogen (TKN), and Total Phosphorous (TP). The effluent produced from SBR systems consistently met the regulatory discharge standards, making it a viable choice for urban wastewater treatment. Moreover, the authors developed and applied a set of scientifically defined criteria to select the most appropriate treatment technology, which included factors such as space requirement, energy efficiency, capital and operational costs, maintenance requirements, and the ability to handle varying inflow characteristics. The study ultimately concluded that SBR technology stands out not only due to its compact design and ability to treat fluctuating flows effectively, but also due to its sustainability and long-term economic feasibility in Indian urban settings. This work contributes significantly to the ongoing discourse on the modernization of India's wastewater infrastructure by promoting the adoption of newer and more adaptive technologies in response to the country's pressing water and sanitation challenges.

D. S. Thanki et. al. (2021), "Evaluating and Comparing Wastewater Treatment Technologies: Performance, Costs, and Sustainability", [3] present a critical and well-structured evaluation of the evolving landscape of wastewater treatment technologies. The authors assert that the increasing burden of water pollution at both local and global levels necessitates the immediate and strategic implementation of modern treatment methods that are not only technically efficient but also environmentally sustainable. With increasing urbanization, the limitations of traditional wastewater treatment systems have become increasingly apparent—particularly their high energy demands, large land footprints, and frequent operational inefficiencies. Thanki et al. (2021) note that such systems, originally designed to handle lower volumes and simpler waste loads, are now struggling to maintain treatment efficacy amid growing pressures. In their study, the authors emphasize the need for a transition toward advanced technologies that can deliver higher removal efficiencies while optimizing resource use. As part of a wider urban sanitation strategy, they highlight the implementation of standardized Service Level Benchmarks (SLBs) aimed at improving municipal service delivery and pollution mitigation. Furthermore, the role of the National Green Tribunal (NGT) is acknowledged for its active involvement in monitoring and regulating the discharge quality in rivers and water bodies, thereby reinforcing the urgency of effective sewage treatment practices. The research conducted by Thanki et al. (2021) focused on comparing multiple technologies, with specific attention given to Sequencing Batch Reactor (SBR) systems, which were selected based on a refined set of criteria including effluent quality, operational flexibility, energy consumption, and space efficiency. SBR technology, according to their findings, proved capable of producing high-quality effluent that meets regulatory discharge standards. The technology exhibited substantial pollutant removal rates, particularly in terms of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Suspended Solids (SS), Ammonia Nitrogen (N), Total Kjeldahl Nitrogen (TKN), and Total Phosphorous (TP), making it a robust solution for urban wastewater management. The study underscores that beyond just treatment performance, long-term sustainability, adaptability to site-specific challenges, and cost-efficiency must also be considered when selecting the most appropriate technology. Overall, this paper contributes meaningfully to the growing body of literature advocating for a strategic shift towards advanced and sustainable wastewater treatment solutions in light of mounting environmental, economic, and social demands.

Rama Narayan Sabat et. al. (2020), "A Comparative Study of Different Sewage Treatment Technologies", [4] underscore the growing importance of adopting advanced and emerging wastewater treatment technologies in order to address the severe and escalating water pollution crisis being experienced globally. Their paper highlights that the traditional sewage treatment systems, while once sufficient, are now becoming increasingly inadequate to meet the demands posed by rising wastewater volumes, rapid urbanization, and evolving pollutant characteristics. According to Sabat and Baliarsingh (2020), conventional systems not only struggle with inefficiency in pollutant removal but also suffer from high operational costs, excessive energy consumption, and land-use challenges, rendering them unsustainable in the long term. The authors emphasize the necessity for sewage treatment systems to be designed and operated in an environmentally responsible manner that aligns with sustainability goals and public health priorities. The authors point out that urban expansion further exacerbates these challenges by compressing infrastructure into increasingly congested spaces, often leading to underperformance and a failure to comply with modern regulatory standards. In response to these challenges, they refer to the Service Level Benchmarks developed to guide improvements in urban sanitation services, with a specific focus on pollution control. The role of the National Green Tribunal (NGT) is acknowledged for its oversight and monitoring of river and stream water quality, adding regulatory impetus to the implementation of advanced treatment solutions. In their comparative analysis, Sabat and Baliarsingh (2020) focus on various treatment technologies but ultimately highlight the Sequencing Batch Reactor (SBR) system as a particularly promising solution. SBR is identified as being capable of producing high-quality treated effluent that complies with environmental standards. Their findings reveal that SBR systems demonstrate superior treatment performance in terms of reducing Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Suspended Solids (SS), Ammonia Nitrogen (N), Total Kjeldahl Nitrogen (TKN), and Total Phosphorous (TP), thereby making it a highly suitable option for urban sewage management. The study effectively bridges the gap between technological performance and environmental compliance, providing critical insights into the factors that must be considered when selecting the most appropriate treatment method. Overall, the work of Sabat and Baliarsingh (2020) makes a significant contribution to the literature by offering a thorough comparison of sewage treatment technologies and reinforcing the need for ongoing innovation, sustainability, and regulatory alignment in the planning and operation of wastewater treatment plants.

Mohd. Najibul Hasan et al. (2019), “Anaerobic and Aerobic Sewage Treatment Plants in Northern India: Two Years Intensive Evaluation and Perspectives”, [5] undertook a robust performance evaluation of seven sewage treatment plants (STPs) across various cities in Northern India over a period of two years. The research included a comparative analysis of two fully aerobic systems — the Sequencing Batch Reactor (SBR) and the Moving Bed Biofilm Reactor (MBBR) — and three hybrid systems combining anaerobic Up-flow Anaerobic Sludge Blanket (UASB) reactors followed by secondary aerobic treatment units such as Polishing Ponds (PP), Aeration + PP, and Down-flow Hanging Sponge (DHS). Their findings revealed that the UASB-based plants followed by simple aerobic units like PP and Aeration + PP consistently failed to meet the surface water disposal standards set by the Ministry of Environment, Forest and Climate Change, Government of India. In contrast, STPs incorporating SBR and MBBR technologies, as well as UASB followed by the DHS process, demonstrated significantly superior treatment efficiency. These systems achieved over 85% removal of Ammonium-Nitrogen (NH4-N) and more than 60% removal of Phosphate-Phosphorus (PO4-P), producing final effluents with concentrations approximating 20 mg/L of BOD_5, 50 mg/L of COD, 20 mg/L of TSS, 10 mg/L of NH4-N, and 5 mg/L of PO4-P. The study also examined methane generation under varying operational conditions, highlighting the energy recovery potential in anaerobic systems. While strictly aerobic technologies like SBR and MBBR yielded higher-quality effluents suitable for surface discharge or reuse, the authors emphasized the practical value of hybrid anaerobic-aerobic systems — particularly the UASB-DHS combination — as cost-effective alternatives for Indian conditions, especially where space and operational simplicity are critical. The research underscores the importance of selecting context-appropriate technologies that balance treatment efficacy, operational cost, and regulatory compliance in urban sanitation planning.

Dharam Vir Singh et. al. (2020), “A Research on Optimized Design of Sewage Treatment Plant (STP)”, [6] explored the essential need for constructing and optimizing sewage treatment plants (STPs) using modern technologies in response to rising environmental challenges, especially the critical shortage of clean water in many Indian regions. The authors highlighted that the increased cement production for conventional infrastructure contributes significantly to CO_2 emissions and environmental degradation, thus necessitating sustainable alternatives like improved STP designs. The study focused particularly on Up-flow Anaerobic Sludge Blanket (UASB), Moving Bed Biofilm Reactor (MBBR), and Sequencing Batch Reactor (SBR) technologies. UASB, once popular for its energy efficiency and biogas generation, has witnessed a decline in adoption due to performance concerns. MBBR, by contrast, combines the advantages of fixed-film and activated sludge processes, using HDPE bio-carriers that promote bacterial growth in a suspended medium, offering high treatment efficiency in compact space with simplified operation. Similarly, SBR technology, which integrates equalization, aeration, and sedimentation within a single reactor basin, is praised for its adaptability to varying flows, and its success in treating both municipal and industrial wastewater. The study primarily assessed the performance of two MBBR-based STPs located in Jhajjar Town, Haryana. Wastewater samples were analyzed for critical physicochemical parameters, including pH, BOD, COD, TSS, turbidity, nitrates, phosphates, total nitrogen (TN), and total phosphorus (TP). The findings confirmed the high efficiency of MBBR systems, with effluent quality consistently meeting discharge standards. Furthermore, treated effluents were reused for agricultural irrigation, and the sludge was effectively repurposed as manure, showcasing environmental and economic benefits. In conclusion, Singh and Jain emphasized the importance of optimized STP design, particularly tertiary treatment, as per National Green Tribunal (NGT) guidelines, to produce high-quality effluent suitable for reuse. Tertiary treatment, as discussed, is capable of removing up to 99% of residual contaminants, including nitrogen and phosphorus, significantly reducing BOD levels and enhancing water quality. The research supports advanced treatment technologies as critical tools in promoting sustainability, resource recovery, and public health protection through improved sewage management systems.

Ankit Sharma et. al. (2019), “Performance Evaluation of Wastewater Treatment Plant Based on SBR Technology with PLC, SCADA System – A Case Study of Rajeev Awas Yojna, Kiron Ki Dhani, Muhana, Rajasthan (India)”, [7] evaluated the efficiency and effectiveness of a sewage treatment plant (STP) operating on the Sequencing Batch Reactor (SBR) technology integrated with Programmable Logic Controller (PLC) and Supervisory Control and Data Acquisition (SCADA) systems. The authors emphasized the growing need for effective wastewater treatment technologies, particularly in regions facing water scarcity and pollution concerns. The study highlights the importance of adopting modern STP technologies that are not only environmentally sustainable but also economically viable and technologically advanced. SBR, as a modern batch treatment system, is known for combining the processes of equalization, aeration, and sedimentation in a single tank. This makes it especially suitable for municipal and industrial wastewater treatment, particularly in areas with variable or intermittent flow. The case study was conducted at the Rajeev Awas Yojna STP in Muhana, Rajasthan, which operates using SBR in conjunction with automation systems such as PLC and SCADA to enhance process control and operational efficiency. Wastewater samples were collected and analyzed for key parameters including pH, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), phosphate, and Total Kjeldahl Nitrogen (TKN). The results of the performance evaluation indicated that the STP effectively met the discharge standards for all tested parameters. The treated effluent was found to be suitable for agricultural reuse, thereby supporting water conservation practices in the region. Additionally, the sludge generated was repurposed as manure and distributed to farmers, contributing to circular economy practices and reducing solid waste disposal issues. In conclusion, Sharma and Pandey demonstrated that SBR technology, particularly when integrated with automated monitoring and control systems, offers a highly reliable, efficient, and adaptive solution for wastewater treatment. Their study reinforced the potential of such modern systems in ensuring effluent quality compliance, resource recovery, and environmental protection. The integration of PLC and SCADA provides real-time monitoring and control, enhancing operational stability and allowing for prompt corrective actions, which is crucial for long-term sustainability of STPs.

Sudha Sippi et. al. (2025), “Effluent quality-based ranking of sewage treatment plants using multicriteria decision making technique”, [8] introduced an innovative framework for evaluating and ranking sewage treatment plants (STPs) in India based on effluent quality performance using a multicriteria decision making (MCDM) approach. The study addresses a critical challenge faced by environmental regulatory agencies—evaluating the performance of numerous STPs across the country in a systematic and scientifically sound manner, especially when direct simulation-optimization models like waste load allocation are impractical due to complexity. The authors proposed a modified Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) as part of their MCDM framework. This technique allowed the researchers to rank 100 STPs across India by integrating both effluent quality indicators and regulatory discharge standards (as specified by the CPCB) within a unified decision matrix. The results demonstrated that small-capacity STPs, especially those using oxidation pond technology, tended to outperform others in terms of effluent quality. Conversely, large-capacity STPs showed improved performance when employing Activated Sludge Process (ASP) technologies. Specifically, the Burhi ka Nagla STP in Agra (1–20 MLD category) and a large-scale STP in Madurai, Tamil Nadu (above 100 MLD) were identified as the best-performing plants in their respective categories. The novelty of this study lies in its integration of regulatory standards with real-time effluent quality metrics in a single analytical framework, allowing for a transparent and comparative assessment of plant performance. To the authors’ knowledge, this is the first instance of a modified TOPSIS method being applied in this context. The findings offer valuable insights for pollution control boards and urban planners, enabling data-driven decisions for improving STP management, resource allocation, and compliance with environmental norms.

Mukesh Ruhela et. al. (2020), “Efficiency of Sequential Batch Reactor (SBR) based sewage treatment plant and its discharge impact on Dal Lake, Jammu & Kashmir, India”, [9] conducted a comprehensive study on the efficiency of a Sequential Batch Reactor (SBR) based sewage treatment plant (STP) located at Brari Numbal and its discharge impact on the physicochemical properties of Dal Lake, Jammu & Kashmir, India. Dal Lake, being the second largest and a prominent tourist destination in the region, is facing serious water quality deterioration due to increasing domestic wastewater generation driven by rapid population growth. The study involved systematic sampling from the inlet and outlet of the SBR-STP as well as from multiple sites along Dal Lake, including upstream, confluence zone, and downstream locations over a period of five months (November 2019 to March 2020). Using standard analytical methodologies, the researchers evaluated key parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH, dissolved oxygen (DO), iron, ammonical nitrogen, and phosphate. The SBR-based plant demonstrated a maximum removal efficiency for BOD at 79.85%, indicating significant treatment of organic load; however, the treated effluent BOD levels still exceeded prescribed discharge standards, signaling incomplete treatment. The removal efficiency for pH was minimal (3.46%), suggesting that the treatment process had negligible effect on this parameter, whereas dissolved oxygen showed a remarkable increase of 851.55%, reflecting improved aeration and oxidation conditions post-treatment. Despite the treatment efforts, the study found that all sampling sites in Dal Lake were polluted, with the confluence zone and downstream areas experiencing elevated pollution levels directly attributed to the discharge of STP effluent. Notably, BOD and COD concentrations increased by 21.39% and 43.29% respectively, along with substantial increases in iron (80.10%), ammonical nitrogen (65.61%), and phosphate (101%) in the downstream waters compared to upstream levels. The findings also pointed to additional untreated wastewater entering the lake, exacerbating the degradation of water quality. The authors concluded that while the SBR technology provides moderate treatment efficiency, the existing STP configuration and operation require further modifications and enhancements to effectively reduce pollutant loads before discharge. This study is significant as it represents the first assessment of the impact of SBR-STP effluent on Dal Lake's water quality and provides critical insights for policymakers and environmental managers seeking sustainable wastewater management solutions in sensitive lake ecosystems.

Nimeshchandra V. Vashi (2019), "Recent Technologies Adopted for Upgradation of Existing Sewage Treatment Plants and for Sewage Reuse and Recycle in Surat, India", [10] presented a detailed study on the recent technological advancements adopted for the upgradation of existing sewage treatment plants (STPs) and for the reuse and recycling of treated sewage water in Surat, India. The research focuses on the integration of advanced biological treatment processes such as Sequencing Batch Reactor (SBR) and Integrated Fixed Film Activated Sludge (IFAS) technologies into older STPs that were originally designed with different treatment systems including Upflow Anaerobic Sludge Blanket (UASB), Conventional Activated Sludge Process (CASP), and Moving Bed Biofilm Reactor (MBBR). The paper highlights how these upgraded technologies enhance the operational efficiency and treatment performance of the STPs in Surat, a rapidly growing urban area with increasing sewage loads. Specifically, the study details the deployment of tertiary treatment units following the biological processes, including dual media filtration after SBR to enable safe reuse of treated effluent for gardening purposes, and ultrafiltration (UF) combined with reverse osmosis (RO) units to treat sewage water to industrial-grade standards for reuse in manufacturing and other industrial applications. These tertiary treatment processes ensure compliance with stringent water quality norms, facilitating the sustainable reuse and recycling of wastewater, thereby reducing the dependency on freshwater resources and promoting water conservation. The authors emphasize that the successful adoption of SBR and IFAS technologies allows for better removal of organic and suspended solids, nutrient reduction, and pathogen control compared to conventional processes, while the combination with membrane filtration units further improves effluent quality to meet reuse criteria. The study underlines the importance of technological upgradation for existing STPs to address the challenges posed by urbanization and escalating water demand, positioning Surat as a case study for cities aiming to modernize their wastewater treatment infrastructure for environmental protection and resource recovery. Keywords associated with the study include Sewage, Conventional Activated Sludge Process (CASP), Moving Bed Biofilm Reactor (MBBR), Sequencing Batch Reactor (SBR), Integrated Fixed Film Activated Sludge (IFAS), Ultrafiltration (UF), Reverse Osmosis (RO), Reuse, and Recycle.

F. Identification of Research GAPS

Despite the extensive comparative analyses and performance evaluations of various sewage treatment plant (STP) technologies such as Activated Sludge Process (ASP), Sequencing Batch Reactor (SBR), Moving Bed Biofilm Reactor (MBBR), and hybrid anaerobic-aerobic systems presented by Sharma et al. (2023), Kaur et al. (2022), Thanki et al. (2021), Sabat et al. (2020), Hasan et al. (2019), Singh et al. (2020), and Sharma et al. (2019), several critical research gaps remain evident that warrant further investigation. First, while the studies provide valuable insights into the operational efficiencies, pollutant removal capabilities, and economic parameters of these technologies, there is a noticeable lack of long-term, real-world performance data particularly under variable and extreme urban load conditions, which are becoming increasingly common due to rapid urbanization and climate variability. Many studies tend to rely on controlled or pilot-scale data, thus limiting the understanding of scalability challenges and performance degradation over extended periods. Second, although the MBBR and SBR systems have been recognized for their superior pollutant removal efficiencies and compact footprints, there is insufficient research on the integration of these technologies with emerging digital tools such as artificial intelligence (AI), machine learning (ML), and advanced sensor networks for predictive maintenance, real-time optimization, and fault detection—areas that are critical for transitioning STPs into smart, autonomous treatment facilities. Third, energy consumption and sustainability are recurrent themes; however, a comprehensive life cycle assessment (LCA) that incorporates embodied energy, greenhouse gas emissions, and sludge management impacts across the full spectrum of treatment technologies remains underexplored. This is particularly significant given the increasing emphasis on carbon footprint reduction and circular economy principles in wastewater management. Fourth, while some studies acknowledge the potential of hybrid systems combining anaerobic and aerobic processes, there is a lack of systematic evaluation of the techno-economic feasibility, environmental trade-offs, and site-specific adaptability of such hybrid configurations across diverse geographic and climatic zones in India and globally. Fifth, the role of tertiary treatment processes, including nutrient recovery and advanced oxidation, as essential complements to biological treatment methods are insufficiently addressed in current comparative studies, despite their importance in meeting increasingly stringent discharge regulations and facilitating water reuse in water-scarce urban areas. Sixth, socio-economic and policy factors influencing technology adoption, including public acceptance, institutional capacities, financing mechanisms, and regulatory enforcement efficacy, are often overlooked despite their crucial role in the successful implementation and scaling of modern STPs. Finally, although the National Green Tribunal (NGT) and other regulatory bodies set rigorous effluent discharge standards, there is a gap in research focusing on the development of adaptive regulatory frameworks that can dynamically respond to evolving urban sanitation challenges, technological advancements, and environmental considerations.

Addressing these research gaps through interdisciplinary, multi-scalar studies incorporating technological innovation, environmental sustainability, socio-economic realities, and policy integration will be vital for advancing the next generation of sewage treatment solutions capable of meeting the complex demands of rapidly urbanizing regions while safeguarding public health and ecological integrity.

III. PROPOSED METHODOLOGY

1) Data Collection:
- Gather technical data on conventional and modern sewage treatment technologies from journals, case studies, and government reports.
- Collect real-world performance metrics from operational treatment plants.

2) Evaluation Criteria:
- Treatment Efficiency: Removal rates of BOD, COD, TSS, and nutrients.
- Cost Analysis: Capital and operational expenses.
- Environmental Impact: Energy consumption, sludge generation, and carbon footprint.
- Operational Feasibility: Maintenance requirements and adaptability to load variations.

3) Comparative Analysis:
- Use statistical tools to analyze performance metrics.
- Conduct a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis of each technology.

IV. CONCLUSION

This review highlights the differences between conventional and modern sewage treatment technologies in terms of efficiency, cost, and sustainability. While traditional methods such as ASP and TF have been widely used, modern techniques like MBR, SBR, and MBBR offer significant advantages in terms of higher efficiency, reduced sludge generation, and improved adaptability to varying wastewater characteristics. However, the selection of an appropriate treatment system depends on factors such as budget constraints, land availability, and environmental regulations. Future research should focus on optimizing these technologies to enhance their effectiveness and reduce operational costs further. By integrating modern treatment techniques with conventional systems, a sustainable and efficient approach to sewage treatment can be achieved, ensuring environmental protection and public health safety.

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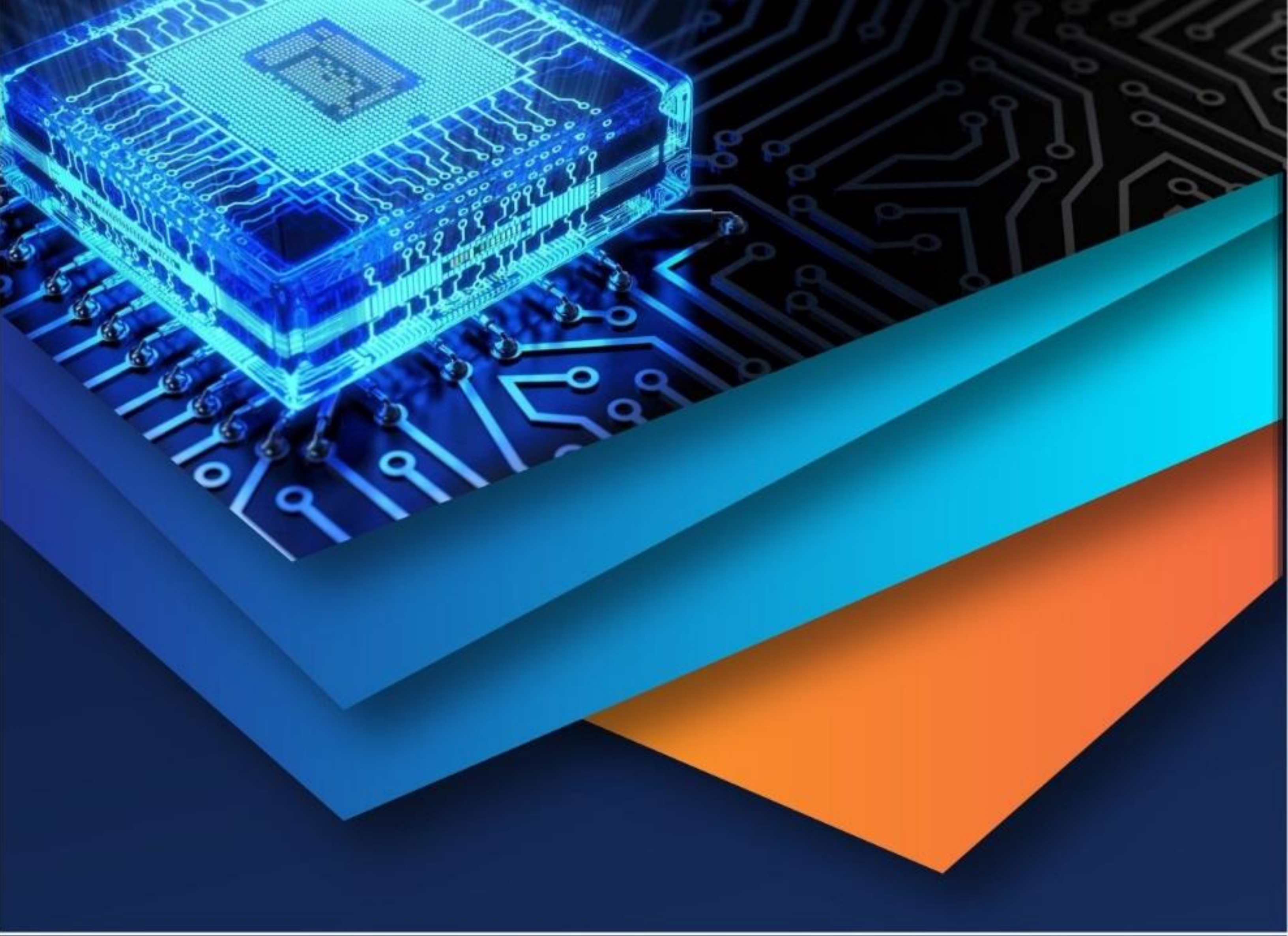

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