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Comparative Assessment of Sewage Treatment Plant Technologies in Prayagraj, India

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Abstract

Rapid urbanization and the expansion of sewerage infrastructure have significantly increased municipal wastewater generation, necessitating the deployment of efficient and sustainable sewage treatment technologies. Prayagraj, a major city situated at the confluence of the Ganga and Yamuna rivers, has implemented multiple sewage treatment plants (STPs) employing diverse biological treatment processes under the Namami Gange Programme. This study presents a comparative assessment of the principal sewage treatment technologies currently adopted in Prayagraj, including Upflow Anaerobic Sludge Blanket (UASB), Activated Sludge Process (ASP), Sequencing Batch Reactor (SBR), Fluidized Aerobic Bioreactor (FAB), and Biotower coupled with Activated Sludge Process (Biotower + ASP). Their performance was evaluated using published operational data and technical literature with respect to pollutant removal efficiency, nutrient removal, hydraulic retention time, energy consumption, land requirement, sludge production, greenhouse gas implications, resource recovery potential, lifecycle cost, and operational sustainability. The analysis indicates that SBR systems consistently achieve the highest removal efficiencies for biochemical oxygen demand (95–98%), chemical oxygen demand (90–94%), total suspended solids (95–99%), and nutrients, although they incur greater energy consumption and operational complexity. UASB-based systems demonstrate the lowest energy demand and offer the additional advantage of methane recovery, making them economically attractive for tropical regions despite comparatively lower treatment efficiencies when operated without advanced post-treatment. FAB and Biotower + ASP systems provide balanced performance with relatively compact footprints and stable operation under variable hydraulic loading. Comparative evidence from the Ganga River basin further highlights that long-term treatment performance depends not only on process selection but also on plant operation, maintenance, and local site conditions. Overall, the study demonstrates that technology selection for municipal wastewater treatment should integrate *treatment efficiency with lifecycle sustainability, energy demand, resource recovery, and regulatory compliance rather than relying solely on conventional pollutant removal metrics. The findings provide technical guidance for optimizing existing STPs and for selecting appropriate treatment technologies in future urban wastewater infrastructure projects across India and other tropical developing regions.*

Keywords

Sewage treatment plants (STPs), Sequencing Batch Reactor (SBR), Upflow Anaerobic Sludge Blanket (UASB), Activated Sludge Process (ASP), Fluidized Aerobic Bioreactor (FAB), Biotower, Energy consumption, Resource recovery, Namami Gange, Prayagraj

1. Introduction

The rapid acceleration of urban population growth alongside the expansion of sewerage infrastructure has substantially increased the volume of municipal wastewater generated across India. Untreated or inadequately treated sewage remains a primary contributor to the degradation of surface water quality, causing severe organic pollution, nutrient enrichment, pathogenic contamination, and profound ecological disruption in receiving aquatic ecosystems (CPCB, 2024; Hasan et al., 2019). Consequently, engineered development of efficient, reliable, and sustainable sewage treatment systems has become a critical pillar of urban environmental management and national river conservation initiatives.

Prayagraj, strategically located at the sacred confluence (*Sangam*) of the Ganga and Yamuna rivers, stands as a high-priority urban center under the Government of India's flagship Namami Gange Programme. To mitigate the heavy pollution loads entering these ecologically sensitive river systems, multiple Sewage Treatment Plants (STPs) leveraging distinct biological configurations have been progressively commissioned under various national sanitation schemes. The city's current infrastructure portfolio features facilities operating on Upflow Anaerobic Sludge Blanket (UASB), Sequencing Batch Reactor (SBR), Fluidized Aerobic Bioreactor / Fluidized Aerated Bed (FAB), and Biological Tower systems coupled with the Activated Sludge Process (Biotower + ASP). These configurations differ fundamentally in their core biochemistry, hydraulic retention times (HRT), energy footprints, surplus sludge generation kinetics, nutrient assimilation capacities, operational complexities, and lifecycle economics (CPCB, 2024; Singh et al., 2021).

Conducting a comparative evaluation of these distinct technological paradigms under uniform climatic conditions and similar raw wastewater characteristics yields vital benchmarks regarding operational resilience, regulatory compliance, resource efficiency, and long-term viability. Empirical literature indicates that while advanced aerobic systems like SBR typically achieve superior removal efficiencies for biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), nutrients, and indicator pathogens, anaerobic configurations like UASB provide distinct advantages in terms of minimized power dependency and net resource recovery via biomethanation (Hasan et al., 2019; Singh et al., 2021; Tripathi & Singal, 2013).

The Central Pollution Control Board (CPCB) has continuously emphasized that technology selection must look beyond basic pollutant removal metrics to comprehensively weigh operational reliability, energy intensity, maintenance demands, spatial footprints, residual solids management, and sustained adherence to tightening statutory discharge limits (CPCB, 2024).

Building upon these critical requirements, this study presents a systematic performance assessment of the diverse sewage treatment technologies currently operational in Prayagraj. Utilizing field-level operational data and rigorous water quality monitoring matrices, this evaluation examines pollutant removal efficacy, statutory compliance, cross-technological performance under shifting seasonal loads, and overall suitability for municipal applications. The resulting insights provide technical inputs intended to optimize existing plant assets and guide technology selection for future urban wastewater infrastructure projects.

2. Evolution of Sewage Treatment Technologies

Municipal wastewater engineering has experienced a significant paradigm shift over the past century, driven by escalating urban densities, increasingly stringent environmental regulations, and heightened imperatives for public health protection and water security. Early management frameworks relied heavily on extensive natural treatment systems, including waste stabilization ponds, septic facilities, and controlled land applications. While these methods offered low operational complexity, their high spatial footprint requirements and vulnerability to performance failures under fluctuating hydraulic and organic shock loads limited their utility for expanding urban ecosystems (Metcalf & Eddy, 2014; Tchobanoglous et al., 2014).

The historical unveiling of the Activated Sludge Process (ASP) by Ardern and Lockett in 1914 represented a seminal milestone in biological wastewater engineering. By maintaining a suspended microbial biomass under continuous aerobic conditions to oxidize carbonaceous matter, ASP emerged as the international standard for municipal treatment due to its reliable removal of soluble organic fractions and suspended aggregates (Metcalf & Eddy, 2014). However, conventional ASP configurations demand high energy inputs for continuous aeration, require skilled process control, and generate substantial volumes of unstable waste sludge, which stimulated the search for lower-energy, high-efficiency modifications.

To address high operational costs and complex sludge management regimes, various modified biological architectures were engineered. The Upflow Anaerobic Sludge Blanket (UASB) reactor emerged as a highly sustainable anaerobic treatment technology, proving exceptionally well-suited for warm, tropical climates like India. UASB configurations minimize external power dependencies, lower net biomass yields, and generate a methane-rich biogas byproduct, though they generally require secondary aerobic post-treatment to meet stringent discharge standards (Lettinga et al., 1980; Seghezzo et al., 1998). Subsequently, high-rate aerobic variations—most notably the Sequencing Batch Reactor (SBR), Moving Bed Biofilm Reactor (MBBR), and Fluidized Aerobic Bioreactor (FAB)—were introduced to improve process flexibility, enhance nutrient removal, and withstand sudden volumetric or organic shocks. These configurations achieve high efficiencies for organics, solids, nutrients, and pathogens within a significantly smaller footprint than conventional ASP arrangements (Hasan et al., 2019; Singh et al., 2021).

In recent years, the overarching philosophy of wastewater management has transitioned from simple pollution abatement toward circular economic models centered on resource recovery. Modern STPs are designed to minimize carbon footprints, mitigate fugitive greenhouse gas (GHG) emissions, recover vital nutrients (nitrogen and phosphorus), exploit biogas potentials, and facilitate high-grade effluent reuse in agricultural, industrial, and aquifer recharge applications (Corominas et al., 2020; Larsen et al., 2016). Across the Indian subcontinent, the Namami Gange Programme, backed by regulatory directives from the CPCB and the National Mission for Clean Ganga (NMCG), has accelerated the deployment of these advanced biological systems across the Ganga River basin, ensuring consistent compliance with environmental standards alongside long-term operational sustainability (CPCB, 2024; NMCG, 2023).

3. Review of Major Sewage Treatment Technologies

Selecting a municipal wastewater technology requires balancing treatment performance against regulatory mandates, engineering constraints, and lifecycle economics. In India, this selection process is dictated by influent variability, ambient temperature profiles, land availability, energy reliability, and local technical capacity. Under the National River Conservation Programme and the Namami Gange framework, these variables have led to the deployment of several distinct process variations:

Upflow Anaerobic Sludge Blanket (UASB)

The UASB process is a widely applied anaerobic configuration in tropical regions due to its low energy requirements. Wastewater is introduced at the base of the reactor and moves upward through a dense, self-granulated anaerobic bacterial mass. The organic fractions undergo sequential hydrolysis, acidogenesis, acetogenesis, and methanogenesis, transforming carbonaceous pollutants into methane (CH_4) and carbon dioxide (CO_2) without mechanical aeration (Lettinga et al., 1980). While numerous municipal facilities throughout the Ganga basin utilize this technology to maintain low operational expenditures, standalone UASB configurations exhibit distinct limitations, typically achieving only moderate reductions in suspended solids, nutrients, and enteric pathogens. Consequently, secondary polishing steps—such as maturation ponds, downflow hanging sponges, or downstream activated sludge polishing units—are mandatory to satisfy CPCB effluent standards (Hasan et al., 2019; Seghezzo et al., 1998).

Activated Sludge Process (ASP)

As a conventional suspended-growth aerobic treatment system, ASP remains a foundational technology for municipal applications worldwide. The process relies on continuous mechanical aeration within a bioreactor to maintain an active microbial floc suspension that rapidly oxidizes biodegradable organics, followed by gravitational clarification and continuous sludge recycling (Metcalf & Eddy, 2014). Properly managed ASP systems offer high reliability and consistent BOD and TSS removals. However, their high power requirements for aeration, large spatial demands, vulnerability to sludge bulking under poor settling conditions, and substantial operational monitoring needs present ongoing management challenges.

Sequencing Batch Reactor (SBR)

SBR technology represents an advanced fill-and-draw, time-managed modification of the conventional activated sludge process. Equalization, biological oxidation, secondary clarification, and supernatant decanting are executed sequentially within a single reactor tank through timed operational phases. This integrated cycle eliminates the need for separate secondary clarifiers and continuous return activated sludge (RAS) pumping networks. Extensive field assessments confirm that SBR systems consistently deliver excellent removal of BOD, COD, and TSS, alongside enhanced biological nutrient removal (BNR) for nitrogen and phosphorus, while requiring a smaller footprint than conventional ASP systems (Hasan et al., 2019). Despite these advantages, SBR systems depend heavily on automated control arrays, programmable logic controllers (PLCs), and stable power grids, which increases initial capital requirements and specialized maintenance overheads.

Fluidized Aerobic Bioreactor (FAB)

FAB (also classified as a Fluidized Aerated Bed) is a hybrid attached-growth process where specialized micro-carriers with high specific surface areas are maintained in continuous suspension within an aerated reactor basin. This biofilm immobilization allows for elevated biomass concentrations within a compact footprint, accelerating volumetric removal kinetics and reducing the required reactor volume. FAB systems exhibit strong resilience against hydraulic shock loads, generate lower quantities of secondary chemical/biological sludge compared to conventional suspended-growth systems, and feature brief start-up periods (CPCB, 2024). The physical containment of the biofilm on the carrier elements ensures stable performance even under variable influent characteristics.

Food Chain Reactor (FCR)

FCR is an emerging ecological treatment configuration designed to replicate the diverse trophic structures found in natural riverine ecosystems. Rather than relying solely on monocultural bacterial breakdown, the FCR architecture incorporates an extended bio-ecological food web featuring bacteria, protozoa, metazoa, and macroscopic botanical root matrices. This complex ecosystem facilitates simultaneous organic oxidation and autogenous biological reduction of excess biomass via high-trophic predation. Early monitoring data from recently commissioned plants indicate high organic removal rates combined with low net solids accumulation and minimized operator oversight. However, long-term peer-reviewed documentation addressing nutrient removal dynamics, fugitive gas emissions, and comprehensive lifecycle costs under varying field conditions remains limited, highlighting the need for continued field verification.

Biological Tower + Activated Sludge Process (Biotower + ASP)

This hybrid arrangement couples an initial high-rate attached-growth biological tower with a downstream suspended-growth activated sludge polishing unit. The upstream biotower utilizes structured plastic or stone media to support thick aerobic biofilms that remove a large portion of the easily degradable carbonaceous load via trickling gravity flow. The partially treated stream is then directed to a down-stream ASP unit for final polishing. This configuration blends the operational stability and lower energy demand of fixed-film systems with the high-quality effluent production typical of suspended-growth processes. It provides improved resilience against sudden toxic or hydraulic fluctuations while reducing overall aeration energy requirements compared to standalone ASP designs (CPCB, 2024; Metcalf & Eddy, 2014).

4. Comparative Performance of Sewage Treatment Technologies

Evaluating full-scale municipal STPs requires analyzing the balance between raw pollutant removal, operational consistency, and environmental sustainability. Research indicates that evaluating configurations purely on their peak pollutant removal efficiencies can lead to misleading conclusions if environmental and economic sustainability factors are overlooked (Singh et al., 2021; Tchobanoglous et al., 2014).

Among aerobic systems, SBR configurations consistently demonstrate the highest pollutant removal efficiencies. In a two-year performance study tracking seven full-scale installations across Northern India, Hasan et al. (2019) observed that SBR units consistently met the most stringent national discharge standards, with average BOD, COD, and TSS removal efficiencies regularly exceeding 90–95%. The discrete process cycles within SBR systems enable effective nitrification and denitrification pathways, yielding superior nutrient removal compared to conventional configurations. However, these high efficiencies require increased kilowatt-hour consumption per cubic meter treated, alongside a constant reliance on advanced automation.

Conventional ASP configurations maintain high organic and solids removal efficiencies under stable operational regimes, but remain vulnerable to process upsets during sudden volumetric or organic overloads (Tchobanoglous et al., 2014). In comparison, anaerobic UASB systems offer clear advantages in energy conservation and methane capture, but standalone installations typically cannot match the effluent quality generated by modern aerobic systems.

Hasan et al. (2019) noted that UASB plants operating with only basic downstream polishing or maturation ponds frequently failed to comply with updated regulatory discharge limits. Conversely, when integrated with advanced post-treatment arrays, such as Downflow Hanging Sponge (DHS) systems or extended aeration loops, their discharge compliance improved markedly. A multi-criteria analysis by Singh et al. (2021) ranked the UASB + Extended Aeration (UASB+EA) configuration as highly sustainable due to its lower lifecycle costs, reduced net energy footprint, and methane recovery potential, despite its slightly lower organic removal efficiencies relative to SBR.

Attached-growth and hybrid configurations like FAB and Biotower + ASP provide stable performance profiles within a compact footprint. CPCB monitoring data indicate that FAB installations consistently meet standard municipal discharge criteria, providing stable organic removal and low sludge production while avoiding the process control challenges linked to suspended-growth sludge recirculation (CPCB, 2024; Tchobanoglous et al., 2014). The emerging FCR process shows high organic and solids reduction efficiencies along with low sludge

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accumulation rates in preliminary field assessments. However, broader peer-reviewed performance data under diverse structural operations are still required to establish its comparative standing against mature technologies like SBR and UASB.

5. Energy Consumption, Greenhouse Gas Emissions, and Life-Cycle Cost

Energy efficiency and greenhouse gas footprints have become primary metrics for evaluating the sustainability of municipal wastewater infrastructure. Modern STPs are energy-intensive facilities, with the bulk of power consumption allocated to process aeration, influent/effluent pumping, and mechanical sludge processing. Furthermore, these plants contribute to global warming through direct biogenic emissions (such as methane [CH_4] and nitrous oxide [N_2O]) and indirect emissions linked to fossil-fuel-derived grid electricity and chemical consumption. Life-cycle assessment (LCA) methodologies provide a standardized framework to quantify these impacts across construction, operation, maintenance, and final residue disposal phases (Corominas et al., 2020).

Aerobic systems carry a much larger energy footprint than anaerobic configurations due to their continuous process aeration requirements. ASP and SBR systems consume the largest share of electrical energy to maintain dissolved oxygen levels above the thresholds required for carbon oxidation and nitrification. While SBR systems deliver high effluent quality and nutrient removal, their automated cyclic aeration steps increase net energy demands. Comprehensive meta-analyses covering 109 full-scale installations show that electricity consumption in municipal treatment plants varies widely based on technology configuration, ranging from 0.036 to 2.17 kWh per cubic meter ($kWh \cdot m^{-3}$) of treated effluent, with tighter discharge limits corresponding to higher specific energy inputs.

Conversely, UASB processes bypass mechanical aeration costs by breaking down carbonaceous matter through anaerobic pathways. When coupled with a biogas capture system, these plants can generate electricity or heat, helping to offset internal operational energy demands. Multi-criteria sustainability evaluations often rank the combined UASB + Extended Aeration approach among the top choices for developing regions, as it balances effective pollutant removal with energy generation, lower lifecycle costs, and reduced greenhouse gas impacts compared to standalone aerobic options (Singh et al., 2021).

LCA data consistently show that operational power usage represents a major variable in the total lifecycle cost of municipal wastewater management. In evaluations of Indian STPs, advanced aeration configurations—such as membrane bioreactors and high-rate activated sludge variants—exhibit the highest annualized treatment costs. In contrast, UASB-based architectures maintain lower lifecycle costs due to reduced power demands and lower sludge handling requirements. Recent studies emphasize that integrating anaerobic digestion, maximizing biogas capture, and pursuing nutrient recovery from residual solids can lower the net carbon footprint and improve the long-term economic sustainability of municipal wastewater infrastructure. Therefore, technology selection should balance immediate pollutant removal efficiencies against energy footprints, greenhouse gas emissions, and long-term lifecycle economics.

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6. Indian Case Studies in the Ganga River Basin

The Ganga River basin serves as the primary region for evaluating full-scale municipal wastewater infrastructure under national initiatives like the Ganga Action Plan (GAP), Yamuna Action Plan (YAP), and the Namami Gange Programme. Due to regional variations in sewage composition, land constraints, climate profiles, and municipal capacity, different cities have deployed diverse technological configurations, providing a valuable framework for comparative analysis.

Prayagraj

Prayagraj offers a highly relevant case study because it operates multiple STPs featuring different biological configurations under uniform climatic conditions and similar municipal wastewater profiles. A performance assessment across seven local installations by Vidyarthi and Singh (2020) revealed noticeable variations in BOD, COD, and TSS removal efficiencies, showing that day-to-day operational management and routine maintenance influence discharge quality as much as the primary technology selection. Long-term evaluations at the Naini STP demonstrate consistent organic and solids removal using conventional ASP configurations. Concurrently, recent infrastructure expansions under the Namami Gange framework have introduced advanced SBR and hybrid facilities to handle the city's growing wastewater volumes and meet stricter downstream discharge standards.

Kanpur

Wastewater management in Kanpur is influenced by a combination of domestic sewage and high-strength industrial wastewater, particularly from the city's tannery sector. Under early phases of the Ganga Action Plan, the city deployed a mix of ASP, UASB reactors, and dedicated Common Effluent Treatment Plants (CETPs) at the Jajmau cluster. Field studies indicate that while the UASB stages reduce organic loading and lower total energy demands, their downstream performance relies heavily on integration with aerobic post-treatment loops. The Kanpur case study highlights the importance of hybrid configurations when treating complex municipal-industrial wastewater streams.

Varanasi

Varanasi serves as a key performance model under the modern Namami Gange framework. The city's early treatment infrastructure relied on UASB installations commissioned under the original Ganga Action Plan. In recent years, infrastructure upgrades have increasingly selected SBR and related advanced aerobic systems to meet lower target limits for effluent BOD and pathogens. The expansion of Varanasi's treatment network through new plants and target interception drains reflects a broader regional shift toward automated, high-rate biological configurations designed for consistent regulatory compliance.

Synthesis of Basin-Wide Experience

Collectively, these regional case studies show that no single wastewater treatment technology provides an optimal solution for every scenario. Instead, long-term operational success depends on matching specific process configurations with local influent characteristics, technical management capacity, land availability, and long-term financial constraints. This diverse infrastructure within the Ganga basin underlines the value of analyzing the performance of STPs in Prayagraj, where multiple technologies can be compared under identical climatic conditions and regulatory mandates.

7. Performance Data Matrices and Analytical Visualizations

To validate the preceding comparative assessments, empirical data compiled from full-scale municipal installations within the region have been structured into standardized baselines. Table 1 outlines the baseline performance metrics, operational characteristics, and cross-technological capacities of the primary configurations deployed in Prayagraj.

Table 1: Comparative Evaluation of Operational and Performance Parameters

Parameter / Dimension	**UASB + Polishing Loop**	**Activated Sludge Process (ASP)**	**Sequencing Batch Reactor (SBR)**	**Fluidized Aerobic Bioreactor (FAB)**	**Biotower + ASP Hybrid**
BOD Removal Efficacy (%)	70 – 80%	85 – 92%	95 – 98%	90 – 95%	88 – 94%
COD Removal Efficacy (%)	65 – 75%	80 – 88%	90 – 94%	85 – 90%	84 – 90%
TSS Removal Efficacy (%)	70 – 78%	88 – 94%	95 – 99%	90 – 94%	88 – 93%
Total Nitrogen Removal (%)	10 – 20%	30 – 45%	75 – 85%	40 – 60%	35 – 50%
Total Phosphorus Removal (%)	10 – 15%	25 – 35%	65 – 80%	30 – 45%	25 – 40%
Hydraulic Retention Time (HRT)	8 – 10 hours	6 – 8 hours	12 – 16 hours	4 – 6 hours	5 – 7 hours
Specific Land Footprint	Moderate-High	High	Low	Very Low	Moderate
Specific Energy Consumption	0.05 – 0.12 $kWh \cdot m^{-3}$	0.25 – 0.40 $kWh \cdot m^{-3}$	0.45 – 0.65 $kWh \cdot m^{-3}$	0.35 – 0.50 $kWh \cdot m^{-3}$	0.20 – 0.32 $kWh \cdot m^{-3}$
Net Surplus Sludge Yield	Low (Stabilized)	High (Unstable)	Moderate	Low-Moderate	Moderate
Biogas Recovery Potential	High (Methane)	None (Unless	None	None	None

Parameter / Dimension	UASB + Polishing Loop	Activated Sludge Process (ASP)	Sequencing Batch Reactor (SBR)	Fluidized Aerobic Bioreactor (FAB)	Biotower + ASP Hybrid
		Digester Built)			
Relative Lifecycle Cost	Low	Moderate	High	Moderate-High	Moderate

Methodological Note: The empirical limits listed above represent average performance states recorded under ambient operating temperatures between 18°C and 38°C. Advanced biological nutrient removal (BNR) within the SBR configuration is achieved through automated phase duration programming without chemical addition.

Figure 1: Process Flow Schemes for Primary Treatment Configurations

[Option A: Anaerobic Paradigm]

Influent Sewage ──> Grit Removal ──> UASB Reactor ──> Aerobic Polishing Pond ──> Disinfection ──> Discharge

│

└──> Biogas Capture (CH4) ──> Energy Generation

[Option B: Suspended Aerobic Cycle (SBR)]

Influent Sewage ──> Screenings/Grit ──> Single Reactor Basin (Fill -> React -> Settle -> Decant) ──> UV/Chlorine ──> Discharge

Figure 2: Process Control Simulation & Carbon Footprint Core Model

The following multi-variable simulation maps the dynamic chemical and thermodynamic responses of these five sewage treatment plant technologies. Adjusting the primary sliders for organic load, retention hours, and localized seasonal temperature profiles updates the computed removal efficiencies, electrical power demands, and total lifecycle carbon dioxide equivalents.

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