

Google Scholar



scopus

Impact factor 6.2

Geoscience Journal

ISSN:1000-8527

Indexing:

- » Scopus
- » Google Scholar
- » DOI, Zenodo
- » Open Access

 www.geoscience.ac



Registered

Different Techniques for MSW Landfill Leachate Characterization and Its Treatment

¹Dushyant Singh Chundawat ²Dr. Ravi Kant Pareek

¹M.tech Scholar, Department of Civil Engineering, Vivekananda Global University, Jaipur

²Associate Professor, Department of Civil Engineering, Vivekananda Global University, Jaipur

ABSTRACT

This study presents a comprehensive evaluation of a Sewage Treatment Plant (STP) using key performance indicators (KPIs) and statistical correlation analysis. Influent and effluent parameters—including Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), total nitrogen (TN), total phosphorus (TP), pH, faecal coliforms, and flow—were monitored over July 2024 to July 2025. Pearson correlation analysis revealed a strong positive relationship between influent COD and BOD ($r = 0.97$), indicating that variations in organic load are closely linked to biodegradable content. Moderate correlation between COD_{in} and TSS_{in} ($r = 0.65$) reflects the contribution of suspended solids to oxygen demand, while flow showed low-to-moderate influence on pollutant concentrations ($r = 0.50$ – 0.58). Effluent COD and BOD maintained strong correlations with influent values ($r = 0.85$ and 0.80), demonstrating that influent characteristics significantly impact treatment performance. The STP exhibited high removal efficiencies, consistently achieving COD, BOD, and TSS reductions above 88%, 95%, and 95%, respectively. These results highlight the effectiveness of the Sequencing Batch Reactor (SBR) system and emphasize the utility of correlation-based monitoring for operational optimization, predictive control, and regulatory compliance in wastewater management.

Keywords: Sewage Treatment Plant, COD, BOD, TSS, Correlation Analysis, Effluent Quality, Wastewater Performance

1. INTRODUCTION

A landfill is an engineered method of disposal that is routinely used to facilitate the systematic and safe disposal of hazardous waste and municipal solid waste (MSW). In many developing countries, solid waste disposal utilizes a primary stage of landfilling which is open disposal [1]. Leachate forms when water penetrates waste in a landfill and transfers certain forms of contaminants [2]. Leachate from municipal landfills contains pollutants which can be classified as belonging to four main groups, which are organic contaminants and substrates, inorganic compounds, heavy metals, total dissolved solids (TDS) and colour [3].

The environmental impacts of untreated or poorly treated leachate is considerable. When leachate is released or discharged and subsequently contaminates soil or groundwater, sources of drinking water could also be exposed to toxic chemicals and pathogenic microorganisms, either directly or indirectly. When leachate is released into surface water bodies the consequences could lead to eutrophication, oxygen depletion, and a loss of biodiversity. Heavy metals and persistent organic compounds or pollutants, may bioaccumulate up through food chains and create large scale developmental issues in humans and the environment; therefore considering and identifying suitable technology to process and treat leachate for a sustainable municipal solid waste management and in a manner that satisfies environmental compliance, nationally and internationally, is highly relevant. Landfill leachate characterization testing methods are equally pertinent to understanding pollution risks and subsequently designing treatment systems. pH, electrical conductivity, total dissolved solids (TDS), chemical oxygen demand (COD), biological oxygen demand (BOD), total Kjeldahl nitrogen (TKN), ammonium-nitrogen (NH₄-N), and heavy metal solids are examples of physical and chemical tests that are often used to characterise substances. When the primary objective is to identify trace levels of organic contaminants or "emerging" pollutants, more sophisticated testing techniques such as gas chromatography-mass spectrometry (GC-MS), high performance liquid chromatography (HPLC), and Fourier transform infrared (FTIR) spectroscopy may be used more often. More tests that focus on toxicity and biodegradability signs may also help us understand how to treat leachate and the environmental risk that comes with it.

Because of its complexity and dynamic character, non-digestive landfill leachate must be treated using a comprehensive method. Typically, leachate treatment techniques are classified into three categories: biological, physicochemical, and advanced or combination procedures. Biological techniques including activated sludge, sequencing batch reactors, and built wetlands are excellent at eliminating biodegradable organic matter and ammoniacal nitrogen, particularly from juvenile leachates. Physicochemical treatment procedures such as coagulation-flocculation, chemical precipitation, air stripping, adsorption, and membrane filtering are often used to remove suspended particles, heavy metals, and refractory chemicals from leachate. AOPs (advanced oxidation

processes), such as Fenton's oxidation, ozonation, and photocatalysis, are receiving interest for their capacity to breakdown persistent organic pollutants [4].

Sewage Treatment Plants (STPs) play a vital role in decreasing environmental pollution by treating municipal and industrial wastewater to ensure compliance with discharge requirements. STP performance evaluations may give insight into the successful removal of organic materials, suspended particles, nutrients, and pathogenic organisms. This assessment often uses performance indicators such as Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), Total Nitrogen (TN), Total Phosphorus (TP), pH, and faecal coliforms, as well as influent and effluent flow rates. The aforementioned characteristics suggest that the treatment procedure is both operationally stable and meets environmental laws designed to preserve recipient rivers.

In its yearly report, the STP shows that COD and BOD levels steadily drop from influent to wastewater levels. As the years went on, COD levels dropped from 319.71 mg/L in the influent to 307.82 mg/L in the influent, and from 34.42 mg/L in the runoff to 23.92 mg/L during the same time period. BOD removal also reflected similar effectiveness, as influent levels of COD ranged from 174.71 to 163.82 mg/L, and were reduced to an effluent concentration of 7.01-6.19 mg/L. These reductions reflected strong efficiency of biological treatment of the influent. The effluent TSS values consistently ranged below 8 mg/L indicating excellent solids separation and sedimentation. The STP also displays good nutrient control, with TN reduced from 11.23-12.99 mg/L to effluent concentrations of 1.29-1.39 mg/L, and TP from 10.37-10.49 mg/L to effluent concentrations of 0.67-0.81 mg/L. The effluent pH remained near neutral, ensuring minimal ecological impact, and faecal coliform levels were significantly reduced, indicating effective pathogen control. Monthly and yearly removal efficiency analyses reveal consistent and improving trends. COD removal efficiency ranged from 88.75% to 92.5%, BOD from 95.89% to 96.75%, and TSS from 95.84% to 96.48%, demonstrating stable and high-performance treatment. Yearly efficiency comparisons further emphasize improvement from 2024 to 2025, with TN and TP removal efficiencies increasing from 88.51% to 89.30% and 92.19% to 93.61%, respectively. Such trends indicate operational optimization, enhanced microbial activity, and effective process control mechanisms. Seasonal variations were also examined to assess the STP's adaptability under different climatic conditions. Seasonal variations were assessed to develop an understanding of the STP's ability to withstand and adapt to a variety of climatic conditions. There was an increase in influent organic load and flow rates during the monsoon and post-monsoon periods, while the STP was able to treat the influent to meet effluent COD, BOD and TSS limits. The monsoon season of 2025 had the lowest effluent COD (22.87 mg/L) and BOD (6.03 mg/L) and very few faecal coliforms (130 MPN/100 mL), indicating effective pathogen removal. The nutrient levels were also consistently lower through the seasons, indicating the STP can treat through seasons without compromising treatment ability.

1.1 MSW LANDFILL LEACHATE

Several things have a big effect on the quality of leachate, such as the type of waste, how old the dump is, the time of year, and the chemicals that are in the waste. The age of a landfill is very important for figuring out the makeup of leachate because leachate from older landfills is usually more steady than leachate from younger landfills. Heavy metals, Total Kjeldahl Nitrogen (TKN), suspended solids (SS), chemical oxygen demand (COD), biological oxygen demand over 5 days (BOD₅), pH, the ratio of BOD₅ to COD, and ammonia nitrogen (NH₃-N) are some of the most important things that can be used to judge leachate. What leachate is like can change depending on how old the dump is. Literature says that leachates from the early stages of a dump have a low pH (less than 6.5), a very high COD (more than 10,000 mg/L, but often higher), a low ammonia nitrogen (less than 400 mg/L), and a high ability to break down naturally. But, leachates from stabilised dumps are said to be alkaline (values > 7.5), have low COD levels (< 4000 mg/L), high ammonia nitrogen levels (values > 400 mg/L), and not biodegrade well, so they are not as easy to treat biologically. The transitional stage of leachate is in between these two stages. It has traits of both the early stage and the stabilised stage.

Rainfall is a big cause of leachate production, as rainwater is the main ingredient in leachate. When it rains and there is wetness in the trash and cover, it makes oxidation, biological activity, and other chemical and physical processes easier that produce leachate. Along with precipitation (infiltration and/or evaporation), surface flow, groundwater infiltration, evaporation, or evapotranspiration, oxidation, and microbial breakdown cause changes in the amount and quality of leachate that is made. So, these factors and processes work together to make leachate with complicated makeup that can change a lot over the life of a dump. This is something that should be thought about when coming up with ways to treat and control leachate.

Table 1. Summary of The Relationship Between Land Fill Age and LL Characteristics [5]

Type of Leachate	Young	Intermediate	Stabilized
Age (years)	<5	5–10	>10
pH	<6.5	6.5–7.5	>7.5
COD (mg/L)	>10,000	4,000–10,000	<4,000
BOD ₅ /COD	0.5–1.0	0.1–0.5	<0.1
Ammonia Nitrogen (mg/L)	<400	NA	>400
TOC/COD	<0.3	0.3–0.5	>0.5
Heavy Metals	Low to medium	Low	Low
Biodegradability	High	Medium	Low
Kjeldahl Nitrogen (g/L)	0.1–0.2	NA	NA
Organic Compound	80% VFA	(5–30%) HA + FA + VFA	HA + FA

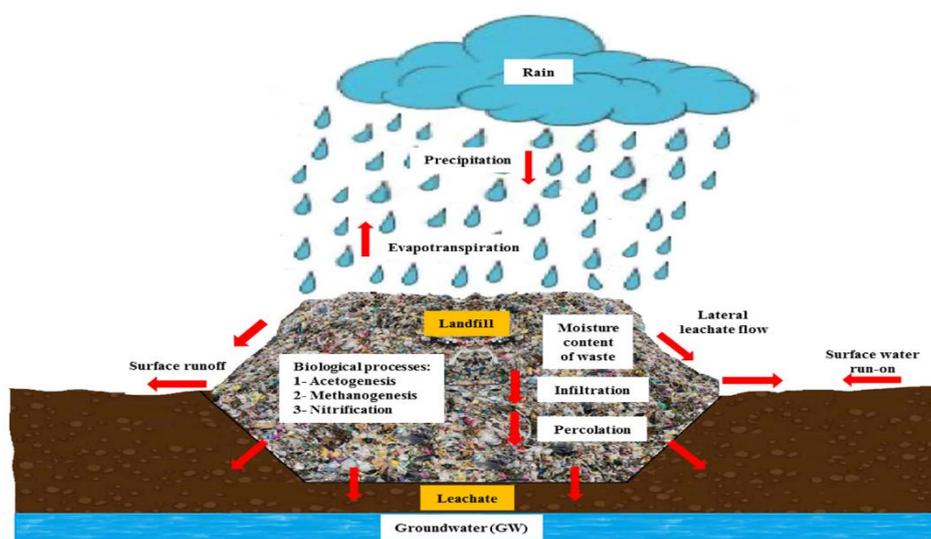


Figure. 1. Landfill leachate [6]

To show this, Figure 1 shows that precipitation is a big part of moving water around in trash, which also moves dirty water to the earth horizontally. The amount and make-up of leachate change over the life of a landfill because of things like rainwater seeping in, the amount of water in the trash, the density of the landfill, and biological and chemical processes. It is common for less packed trash to produce more leachate because it filters less quickly.

The biological and chemical reactions that occur within the landfill can be divided into four stages, as illustrated in Figure 2:

1. Aerobic stage
2. Anaerobic and acidogenic stage
3. Unstable methanogenic stage
4. Stable methanogenic stage

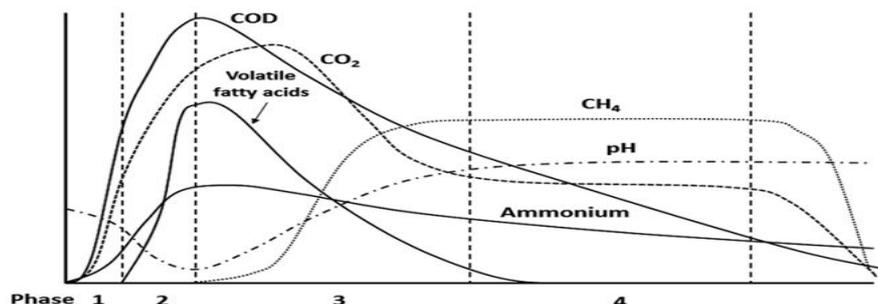


Figure. 2. Scheme of biological treatment of LL. 1 = aerobic stage; 2 = anaerobic acidogenic stage; 3 = unstable methanogenic stage; 4 = stable methanogenic stage [7]

Landfills are experiencing a series of decomposition processes driven by both aerobic and anaerobic bacteria. The aerobic process is the main process whereby aerobic bacteria initiate the decomposition of waste products using oxygen available in the landfill site. During the aerobic process, aerobic bacteria decompose organic material to produce several decomposition products including sulfate, nitrate, carbon dioxide (CO₂) and water (H₂O). The duration of the aerobic process is relatively short, only lasting for a few days due to the rapid consumption of oxygen [8]. Aerobic degradation produces a variety of biodegradable chemicals. When the available oxygen supply is depleted, the reaction will shift to anaerobic decomposition. The anaerobic decomposition process involves anaerobic bacteria that exist in the absence of oxygen, and as a result, it is characterized by some type of acid fermentation. The pH levels for landfill leachate can drop to approximately ~5.5–5.6 while volatile fatty acids (VFA) and CO₂ are also being generated. The pH or accumulation of acids inhibits any further unstable methanogenic phase by converting CO₂ and VFA into methane. The anaerobic study of decomposition can take a duration of several months to the occurrence of two-years with a rising pH resulting from ongoing decomposition of organic waste.

The stable methanogenic stage is the final phase in which additional methane is produced after all biodegradable organic carbon has been used. The stable methanogenic stage can last between 15 and 20 years and is considered the end of the biodegradation process occurring in the landfill. Any methane produced from the stable methanogenic phase can be recaptured by using it as a renewable energy source as fuel or electricity. Besides estimating microbial processes, the estimation of leachate production is another critical aspect of landfill management. The Hydrologic Evaluation of Landfill Performance (HELP) model is another commonly used method to estimate leachate production. The HELP computerized model depends on seven inputs: precipitation, surface runoff, evaporation, variations in the water content in the landfill cap and variations in the water content in the waste material. The HELP model estimates leachate produced during the time the landfill is operated as input parameters [9].

2. RELATED WORK

This section reviews existing studies on MSW landfill leachate, its characterization techniques, treatment methods, and research gaps.

2.1 Municipal Solid Waste (MSW) and Landfill Overview

Khoiron et al. (2020) explored the environmental and public health ramifications of municipal solid waste (MSW) landfilling. They identify three physical states of landfill waste: solid, liquid (leachate), or gas, and landfill waste pollution can threaten the air, soil, and water. I found that the primary environmental pollutants identified by my authors were heavy metals (Cd, Cr, Fe, Ni, Pb, Zn, Mg), gases (methane and H₂S), and pathogenic microorganisms (Coliform, Clostridia, Shigella) and their public health effects included: skin and eye irritation, gastrointestinal distress, allergies, or nasal irritation [10]. **Nanda and Berruti (2021)** offered an extensive analysis of municipal solid waste (MSW) management and disposal practices, naming the United States, China, and India the largest generators of waste. They indicated that demographics of waste are proportional to population income levels, whereby low to middle class populations tend to generate mainly organic waste compared to high-income populations producing paper, metal, and glass. Even though it is not an ideal method, landfill disposal is still preferred, acting like ecological reactors where waste goes through physical, chemical, and biological processes. They emphasized advancement in the landfill liner, leachate collection, gas recovery, and bioreactor landfills as valuable contributions to sustainable waste management and environmental protection [11]. **Noor et al. (2013)** assessed energy recovery from municipal solid waste (MSW) in Malaysia, emphasizing its capability to reduce greenhouse gas (GHG) emissions. The investigation indicated that MSW generation increased from 5.6 million

tonnes in 1997 to over 8 million tonnes in 2010, with a prediction of more increases. In spite of only six active sanitary landfills operating, five were recovering methane for energy. With over 60% of biodegradable material, Malaysian landfills have tremendous potential for landfill gas (LFG) recovery, achieving economic, environmental, and social gain through the generation of electricity and carbon credits, job growth, and supporting sustainable development initiatives [12]. **Singh et al. (2011)** assessed the feasibility of converting municipal solid waste (MSW) into energy in India, and noted its viability as a viable solution to energy shortages and for alleviating the environmental impact. Rapid urbanization and industrialization in India that produce thousands of tonnes of MSW every day have highlighted numerous management issues that require assistance. The assessment examined the different aspects of the municipal solid waste management (MSWM) in generation, collection, processing and disposal, which produced some issues with reference to the current state of infrastructure and technology. Additionally, it provided a historical perspective on waste-to-energy systems, potential uses, benefits and problems, while referencing some valuable knowledge on sustainable MWS management. It could provide some useful insights for decision makers and investors regarding the potential environmental, economic, and technological opportunities in an Indian context [13]. **Ahmad et al. (2018)** regards the management of municipal solid waste (MSW) landfilling and leachate treatment, focusing on the issues surrounding increasing waste generation and eventual acceptance to a landfill. These authors stressed that traditional dumping sites could be a pathway to pollution to the environment via leachate and gases resulting from disposal of solid waste which could leach into, or vaporize to the atmosphere, impacting groundwater or surface water. Leachate should be construed as a direct discharge contaminating liquid due to the degradation of solid organic waste and percolation of rainwater which needs to be managed. The authors also reviewed landfill management methods, production of leachate, characterization of leachate and treatment of leachate, while espousing that sustainable landfilling is part of integrated solid waste management methods [14].

2.2 Landfill Leachate: Formation and Characteristics

Jamrah et al., (2024) analyzed landfill leachate (LL) treatment, revealing LL contains complex toxic and refractory pollutants where the characteristics vary with landfill age and biochemical processes, contributing to treatment challenges. The authors argued that traditional single treatment methods such as biological, chemical or physical processes might not meet environmental standards. They reported that combined treatment processes—such as Fenton with adsorption and membrane bioreactor (MBR) with nanofiltration (NF)—achieve superior COD removal efficiencies up to 99% and significantly improve biodegradability, increasing BOD5/COD ratios from 0.084 to 0.82. The paper concludes that integrated treatment systems provide efficient pollutant mineralization and are essential for sustainable landfill leachate management [15].

Abdel-Shafy et al. (2024) reviewed the sources, composition, and treatment of landfill leachate, emphasizing its environmental hazards. Leachate, generated from liquid percolation through stockpiled waste and organic decomposition, contains soluble organics, inorganic compounds, heavy metals, and xenobiotic organics. Concentrations are high during the early acid phase and stabilize in the methanogenic phase, though ammonia remains persistent. The study discussed the impacts on soil and water and reviewed treatment methods, including leachate recycling with domestic sewage, biological processes (aerobic and anaerobic), chemical and physical procedures (oxidation, adsorption, coagulation), and membrane technologies, highlighting their efficiency in producing high-quality effluent [16]. **Zhang et al. (2023)** examined the mechanisms of landfill leachate formation, as well as leachate resulting environmental and health risks. The authors note that leachate composition and characteristics are complex and depend largely on type of municipal solid waste (MSW) that's generated--more specifically, the amount of kitchen waste. In this respect, the more kitchen waste is present, the higher initial water content available to waste, the better water retention characteristics of the waste, and higher leachate volatilization. The authors also analyzed characteristics of degradation of leachate at different stages, compound specific transformation rate, and factors affecting leachate yield. An understanding of such principles are useful for purposes of leachate generation prediction, designing leachate treatment technologies, and the characterization of physicochemical properties for environmental management [17]. **Iskander et al. (2018)** investigated the existence, attributes, and methods of removing ultraviolet quenching substances (UVQS) from landfill leachate. Landfill leachate contains an assortment of chemical contaminants, some of which are resistant organic chemicals. Organic chemical contaminants include humic acids, fulvic acids, and hydrophilics that reduce UV transmittance and lead to challenges of treating the wastewater through disinfection. Co-treatment with municipal sewage is often part of the disposal plan for landfill leachate; however, biological treatment options are often unable to successfully remove or reduce UVQS. In this article, the authors point out that chemical, electrochemical, and/or physical treatments would achieve better UVQS removal efficiencies than biological treatment methods. Combining treatment methods will tend to achieve the optimum UVQS removal efficiencies, and it is critical to recognize and manage UVQS for sewage and leachate treatment systems [18]. **Gong et al. (2024)** examined the biological and physical characteristics of fouling within landfill leachate treatment processes. Fouling is observable during treatment as biofilm develops on both collection pipelines and other surfaces, which can

compromise the integrity of leachate transport and increase frequency of maintenance. The study showed that anaerobic and aerobic fouling published both structure and function of microbial communities observed, and biological processes including carbon fixation, methanogenesis, nitrification and denitrification. Anaerobic and aerobic fouling also resulted in accumulation of pathogens and antibiotic resistance genes (ARGs) beyond that associated with leachate, causing concern relative to the environment and fouling [19].

2.3 Techniques for Leachate Characterization

Teng et al. (2021) conducted a review of landfill leachate including the characterization as complex, and organic, as well as the environmental explicability. The literature review established improvements in physicochemical characterization and advances in the literature with spectroscopic characterization of landfill leachate properties. The review also evaluated treatment technologies, especially advanced oxidation processes, as they are effective in degrading more recalcitrant organics. Finally, the review evaluated the limitations and challenges associated with wastewater treatments and the socio-economic and environmental readiness of the treatment process and offered summary opportunities. Ultimately, the physicochemical characterization of landfill leachate properties is very relevant and important for future research in new treatment options to mitigate the impacts to ecological, environmental, and human health [20].

Baettker et al. (2020) examined the efficacy of traditional and non-traditional characterization parameters for landfill leachate from municipal sources. They pointed out that one cannot characterize leachate based solely upon standard physicochemical parameters, and treat the characterization adequacy as entirely resolved. Their use of an inert chemical oxygen demand (COD) test, their length-of-exposure test, and spectroscopic techniques, namely, fluorescence and UV-Vis absorbance, to characterize leachate biodegradability and transition labile to traditional refractory dissolved organic matter (DOM) was a compelling use of both traditional and non-traditional characterization parameters. The non-conventional parameters were inexpensive and a much less complicated than conventional parameters; and the application of both conventional and non-conventional parameters provided the crucial, more granular characterization and clarification for treatment process selection and long-term waste management [21]. **Roy et al. (2018)** reviewed the characterization and treatment of leachate generated from composting organic wastes. While composting stabilizes organic material, it produces large volumes of leachate containing biodegradable organics, nutrients, heavy metals, and plasticizers, posing environmental risks. The study discussed treatment technologies, including membrane bioreactors and reverse osmosis, achieving high removal efficiencies for NH_4^+ , COD, and TSS, yet the treated effluent remains hazardous. The review emphasized the need for combined biological and advanced oxidation processes to produce safely disposable effluents. It highlighted gaps in effective treatment strategies, particularly given the growing number of composting facilities worldwide [22]. **Rathnayake and Herath (2018)** reviewed various landfill leachate treatment techniques, emphasizing the high contamination potential of leachate due to dissolved and particulate organics, inorganics, heavy metals, ammonium ions, and xenobiotic compounds. Leachate composition varies with waste type and age, making treatment challenging. Biological methods such as activated sludge (AS), sequencing batch reactors (SBR), up flow anaerobic sludge blankets (UASB), and oxidation ponds are effective for young leachate but less so for mature leachate. Physicochemical approaches, including activated carbon adsorption, chemical precipitation, and reverse osmosis (RO), are commonly applied. Combined biological-physicochemical systems, e.g., AS with RO, achieve near-complete COD and $\text{NH}_4\text{-N}$ removal, offering optimal treatment performance [23]. **Naveen et al. (2017)** studied the physical, chemical, and biological properties of urban municipal landfill leachate that was of medium age (5- 10 years). They found elevated nutrient values (COD 2000 - 3000 mg/L, nitrogen ~2000 mg/L) and accumulation of significant heavy metals, indicating primarily municipal solid waste inputs. They found that while there were different communities of bacilli, community differences were associated with different redox conditions. According to their Leachate Pollution Index (LPI) and Water Quality Index (WQI) assessments, the leachate was inconsistent and there is a risk of damage to the environment or nearby water resources. In general, this establishes the utility of chemical and microbial characterization to evaluate risk of contamination and management practices for landfill leachate [24]. **Ergene et al. (2022)** analyzed landfill leachate from 220 landfills in 46 countries, executing a multilayered assessment through multivariate statistical methods such as cluster analysis, principal component analysis (PCA), and regression analysis. The authors determined strong correlations among leachate parameters and found the PCA determined that inorganic parameters were highly correlated and quite independent of the waste state of biodegradation. Variability of organic, inorganic parameters, and salts was related to landfill parameters like landfill type and waste composition. This study advances our understanding of leachate transport, biodegradation and treatment potential by understanding landfill leachate behavior and by developing steps to highlight effective and beneficial approaches for monitoring and management for municipal solid waste landfills more broadly in the future [25]. **Nath and Debnath (2022)** reviewed landfill leachate treatment technologies, emphasizing that leachate, with high COD and BOD and toxic organic and inorganic constituents, poses a major environmental threat. The study categorized treatment methods into biological, physicochemical, and hybrid approaches, highlighting that standalone methods often fail to meet

disposal standards. Integrated biological–physicochemical systems were found most effective in achieving stringent removal of COD, BOD, and ammonia nitrogen. The review also discusses the influence of landfill age and leachate composition on treatment selection and underscores technological advancements and combined strategies as essential for sustainable leachate management and environmental protection [26].

3. MATERIALS AND METHODS

This study systematically evaluates the performance of the Sewage Treatment Plant (STP) over the period July 2024 to July 2025. Influent and effluent parameters COD, BOD, TSS, TN, TP, pH, flow, and faecal coliform were collected and subjected to rigorous validation and preprocessing. Pollutant removal efficiencies were calculated on a monthly, seasonal, and annual basis to quantify treatment effectiveness. Descriptive statistical analyses were performed to assess variability, operational stability, and influent–effluent relationships. Pearson correlation analysis identified key influent drivers affecting effluent quality. Seasonal trends and flow variations were also examined to evaluate disinfection performance, process optimization, and the overall operational reliability of the STP.

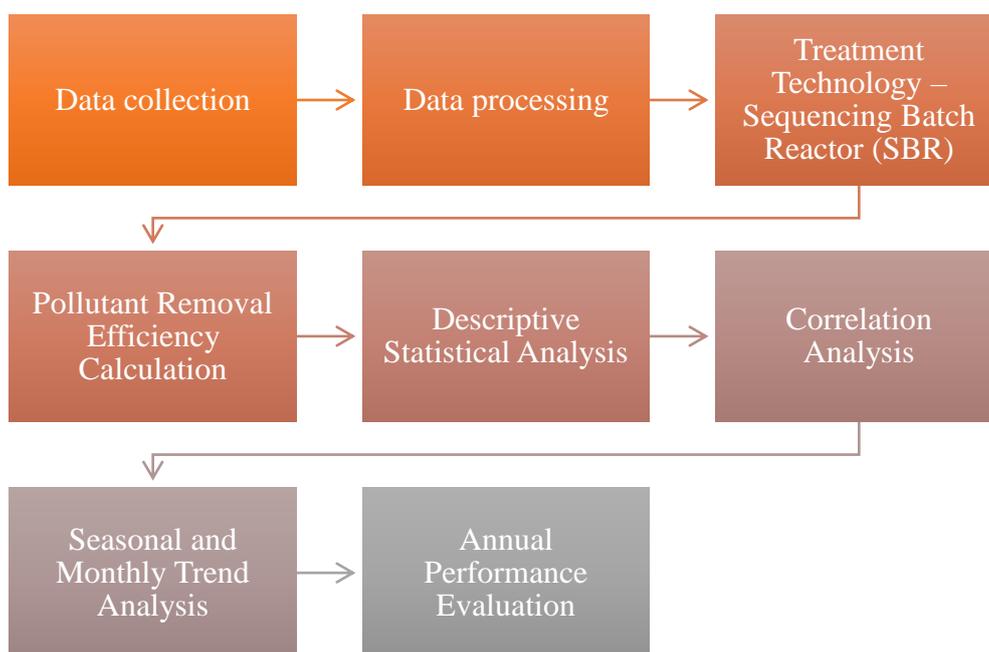


Figure 3: Methodology Flowchart (Source: author)

3.1 Data Collection

Data were collected directly from the STP operational records and laboratory analyses. Both influent and effluent parameters were measured, including COD, BOD, TSS, TN, TP, pH, flow (in MLD), and Faecal Coliform (FC in MPN/100 mL). The data collection period was divided into two windows: 2024 (July–December) and 2025 (January–July). Seasonal classification was performed to account for climatic effects: Monsoon, Post-Monsoon (2024), Winter, Summer, and Monsoon (2025). The collected data provided a comprehensive dataset for evaluating the STP performance under varying operational and seasonal conditions.

Table 2: Wastewater Parameters and Units

Parameter	Measurement Type
COD, BOD, TSS	mg/L
TN, TP	mg/L
pH	Inlet & Outlet
Flow	MLD
Faecal Coliform	MPN/100 mL

3.2 Data Preprocessing

The collected data was prepared satisfactorily prior to being analyzed. Data reliability and accuracy were ensured through preprocessing. All measurements were screened for missingness or inconsistencies. Identified outliers

were based on descriptive statistics (minimum, maximum, and standard deviation). For COD_{in}, values ranged from 235 mg/L to 290 mg/L in 2024 and 238 mg/L to 290 mg/L in 2025. COD_{out} ranged from 22 mg/L to 35 mg/L in 2024 and 15 mg/L to 28 mg/L in 2025. All units were standardized (mg/L for concentrations, MLD for flow), so that a uniform basis could exist. All monthly and seasonal datasets were appropriately aligned for comparative trend analysis, ensuring a consistent basis for the assessment of pollutants removal efficiencies across temporal periods.

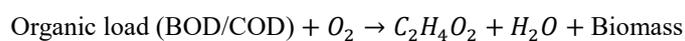
3.3 Treatment Technology – Sequencing Batch Reactor (SBR)

The Sequencing Batch Reactor (SBR) is a versatile and efficient process for wastewater treatment based on an activated sludge treatment process in a time-sequenced batch cycle. In one tank, the wastewater treatment requirements are addressed in sequential stages of treatment, providing a process that is very efficient and versatile at relatively low cost, particularly where the influent flow rate varies greatly. The phases of the SBR cycle generally consist of:

1. **Fill:** The tank is filled with wastewater, typically from the influent system.
2. **React (Aeration):** In this phase, the wastewater is aerated, allowing microorganisms to oxidize organic pollutants, degrade biochemical oxygen demand (BOD), chemical oxygen demand (COD), and perform nitrification. The microorganisms also convert ammonium ions (NH₄⁺) into nitrate (NO₃⁻) through aerobic processes.
3. **Settle:** The aeration is stopped, and the mixed liquor settles under gravity, allowing solid particles, including biomass, to separate from the treated water.
4. **Decant:** The clarified supernatant (treated water) is removed from the tank, leaving the settled solids (sludge) behind.
5. **Idle:** This phase allows for tank preparation for the next cycle, including sludge wasting if necessary.

The following reaction formulas describe the primary biochemical processes that occur during the **React (aeration) phase** of the SBR cycle:

- Organic load degradation (BOD/COD removal):



- In this reaction, organic pollutants are oxidized by oxygen, forming biomass and water.

Nitrification (ammonia to nitrate conversion):



Here, ammonium ions (NH₄⁺) are converted to nitrate (NO₃⁻) with the consumption of oxygen.

The treatment process in an SBR system has demonstrated high pollutant removal efficiencies, with results indicating over 92% COD removal, 96% BOD removal, and 96% TSS removal. Additionally, the system is highly effective in removing nutrients, with approximately 89% total nitrogen (TN) and 93% total phosphorus (TP) removal. The SBR system also significantly reduces faecal coliform levels, ensuring compliance with discharge standards.

3.4 Pollutant Removal Efficiency Calculation

The removal efficiency of each parameter was calculated to quantify the effectiveness of the STP. The standard formula used is:

$$\text{Removal Efficiency (\%)} = C_{in} - C_{out} / C_{in} \times 100$$

Where:

- C_{in} = Influent concentration of the parameter
- C_{out} = Effluent concentration of the parameter

The removal efficiencies for COD, BOD, TSS, TN, and TP, were evaluated on a monthly, seasonal, and yearly basis. For example, at COD removal efficiency for July 2024, calculated using the above equation, was 88.97%. This process is used to identify periods of lower and higher treatment efficiencies, and also hints toward operational stability, as well as opportunities for improvement.

3.5 Descriptive Statistical Analysis

To understand the range and centre trend of key factors, descriptive statistics were used. For the input and output streams, the mean, standard deviation, minimum, and highest numbers were found. There was a mean COD_{in} of 265.84 mg/L and a standard deviation of 12.79 mg/L in 2024. Mean COD_{out} was equal to 28.62 mg/L with a standard deviation of 3.13 mg/L. BOD_{in} and TSS_{in} concentrations were analyzed similarly for the influent and effluent. Descriptive statistics helped indicate variability of influent composition to the STP, indicated what could be considered consistent quality of effluent, and confirmed that the STP operated as designed with variability in loading.

3.6 Correlation Analysis

We found the Pearson correlation coefficients (rrr) between the factors of the influent and effluent to see how the quality of the influent changes the results of the wastewater. This is the method used:

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}}$$

Where:

X_i and Y_i are individual observations of the variables

\bar{X} and \bar{Y} are their mean values

There was a strong correlation between COD_{in} and BOD_{in} ($r = 0.97$) as well as COD_{out} and BOD_{out} ($r = 0.93$), proof that influent organic load was an important indicator of effluent quality. There were moderate correlations between TSS_{in} and both COD_{in} ($r = 0.65$) and BOD_{in} ($r = 0.62$). This analysis was helpful in identifying the most important influent drivers affecting treatment performance.

3.7 Seasonal and Monthly Trend Analysis

Monthly and seasonal variations were analyzed to evaluate the operational stability and efficiency of the STP under different climatic conditions. For example:

- COD_{out} decreased from ~34 mg/L in the 2024 monsoon to 22.87 mg/L in the 2025 monsoon.
- BOD_{out} remained consistently low (6–7 mg/L), while TSS_{out} ranged 7.34–7.96 mg/L.
- Faecal coliform counts decreased from 185 MPN/100 mL (post-monsoon 2024) to 130 MPN/100 mL (monsoon 2025).

Seasonal and monthly analysis also included flow rate trends (15.68–17.97 MLD), helping assess STP capacity, disinfection effectiveness, and process resilience during high-flow or high-load periods.

3.8 Annual Performance Evaluation

Yearly averages were compared to quantify improvements in treatment efficiency between 2024 and 2025. Significant improvements were observed:

- COD removal: 89.23% → 92.23%
- BOD removal: 95.98% → 96.50%
- TSS removal: 95.93% → 96.28%
- TN removal: 88.51% → 89.30%
- TP removal: 92.18% → 93.61%

These improvements indicate enhanced operational processes, optimized sludge management, improved aeration, and more effective microbial disinfection during 2025.

4. CASE STUDY

It was part of the National Mission for Clean Ganga program and finished in May 2024. The Bareilly Sewerage project included Interception and Diversion (I&D) and Sewage Treatment Plant (STP). For the city of Bareilly, the project's goal was to clean up and treat garbage. For the whole city's waste to be cleaned, the project included three STPs: a 42 MLD STP on Bisalpur Road, a 20 MLD STP near Chaubari Nala, and a 1 MLD STP at Air Force Nala. In line with the 42 MLD, 20 MLD, and 1 MLD STPs, the project had three pumping stations and a 12.52 MLD lifting station [27].

The cost of Bareilly's sewer project will be approximately Rs 2.72 million and will be a significant investment in infrastructure improvements. There will be an estimated 16,391 meters of sewer lines and 120 meters of rising mains. In addition, it will consist of 15 I&D structures that will temporarily capture and divert the wastewater for domestic and industrial sources to wastewater treatment facilities. The infrastructure directly improves Bareilly's wastewater management system by ensuring that untreated sewage is properly treated prior to discharge into any water bodies - consistent with the aims of the National Mission for Clean Ganga. With the first trial run of the STPs having already successfully occurred, by June 2024 the project will be connected to drains. Overall, the completion of this project demonstrates a significant step forward in progressing wastewater management in the area, improving the quality of rivers and waters overall, and contributing to the National Mission for Clean Ganga's desired outcome of rejuvenating and restoring the Ganga river. This project has improved the wastewater management infrastructure for the City of Bareilly, while also fulfilling the greater environmental and public health objectives of the National Mission for Clean Ganga.



Figure 4: Site image [27]

As of May 2024, the construction of the Bareilly Sewerage (Interception and Diversion [I&D] and Sewage Treatment Plant [STP]) project has been completed under the National Mission for Clean Ganga initiative. The core objective of this ambitious project is to deal with wastewater treatment and pollution control in the city. Three sewage and treatment plants (STPs) being installed are:

- 42 MLD STP near Bisalpur Road (Latitude: 28.3477° N, Longitude: 79.4251° E),
- 20 MLD STP near Chaubari Nala (Latitude: 28.3672° N, Longitude: 79.4299° E),
- 1 MLD STP near Air Force Nala (Latitude: 28.3594° N, Longitude: 79.4361° E).

The plants will therefore establish a complete sewage treatment system in the area. In addition, three primary pumping stations of 42 MLD, 20 MLD, and 1 MLD respectively, together with a 12.52 MLD lifting station, will assist in the collection and transmission of sewage. The estimated cost of the Bareilly sewerage project is Rs 2.72 million and will include major infrastructure works in laying 16,391 meters of sewer lines and 120 meters of rising mains. The project also plans to build 15 I&D structures which will be used to intercept and divert the wastewater from different sources straight to the treatment plants. This infrastructure will vastly improve the wastewater management system of Bareilly and ensure that untreated sewerage is satisfactorily treated before it is discharged to water bodies, as part of the National Mission for Clean Ganga. Following the successful completion of the first trial of the STPs, the project will be connected to drains by June 2024. This would complete a significant milestone in the region's wastewater management efforts aimed at improving local river water quality, in line with the larger mission to rejuvenate the Ganga river. The project has delivered vital infrastructure for Bareilly and contributed to the wider environmental and public health mission of the National Mission for Clean Ganga.

5. RESULT AND DISCUSSION

Data from the 20 MLD Sewage Treatment Plant adjacent to Chaubari Nala, Uttar Pradesh, between June 2024 and June 2025, indicates that the plant is consistently performing well with a high level of efficiency. The influent and effluent parameters of the key constituents—including COD, BOD, TSS, nutrients, and faecal coliforms—were evaluated to monitor treatment efficiency, seasonal variability, and operational stability.

Table 3: Annual Summary Sewage Treatment Plant KPI

Parameter	2024 (Jul–Dec)	2025 (Jan–Jul)
COD In (mg/L)	319.71	307.82

Parameter	2024 (Jul–Dec)	2025 (Jan–Jul)
COD Out (mg/L)	34.42	23.92
BOD In (mg/L)	174.71	176.82
BOD Out (mg/L)	7.01	6.19
TSS In (mg/L)	192.56	199
TSS Out (mg/L)	7.83	7.4
TN In (mg/L)	11.23	12.99
TN Out (mg/L)	1.29	1.39
TP In (mg/L)	10.37	10.49
TP Out (mg/L)	0.81	0.67
pH In	8.09	8.33
pH Out	7.26	7.56
Faecal Coliform Out (MPN/100ml)	175.1	151.97
Flow In (MLD)	15.68	17.81
Flow Out (MLD)	15.73	17.75

The annual review of Sewage Treatment Plant (STP) Key Performance Indicators (KPIs) demonstrates the efficiency associated with the treatment process in pollutant removal. The influent Chemical Oxygen Demand (COD) appeared to decrease slightly from 319.71 mg/L in 2024 to 307.82 mg/L in 2025, while effluent COD decreased significantly from 34.42 mg/L to 23.92 mg/L, indicating treatment effectiveness in organic load removal. For Biochemical Oxygen Demand (BOD), influent levels decreased from 174.71–176.82 mg/L, while effluent levels decreased to 7.01–6.19 mg/L, demonstrating excellent biodegradation. Removal of Total Suspended Solids (TSS) was also stable, with effluent levels consistently below 8 mg/L. Additionally, nutrient removal was effective, with Total Nitrogen (TN) and Total Phosphorus (TP) concentrations reduced to below 1.5 mg/L and 0.8 mg/L, respectively. Ph levels were neutral in effluent and faecal coliform concentrations were significantly reduced. Compliance with discharge standards was also evident throughout the year from stable flow rates and continued efficient operation of the Plant.

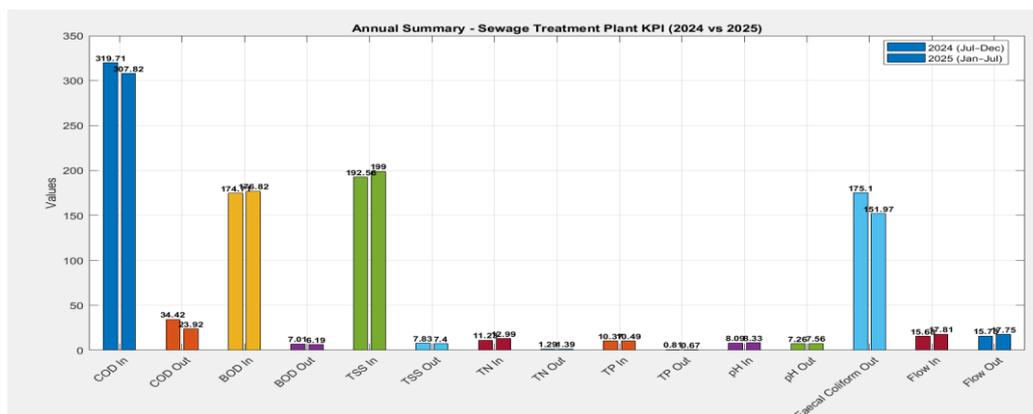


Figure 5: Annual Summary Sewage Treatment Plant KPI

Table 4: Monthly Removal Efficiency

Month	COD_Removal_%	BOD_Removal_%	TSS_Removal_%
2024-07	88.97	95.91	95.84
2024-08	89.32	96.1	95.84
2024-09	88.98	96.02	95.94
2024-10	88.75	95.89	95.9
2024-11	90.15	96.03	96.15

2025-03	92.37	96.22	96.03
2025-04	92.17	96.75	96.3
2025-05	91.77	96.52	96.44
2025-06	92.44	96.47	96.29
2025-07	92.5	96.75	96.48

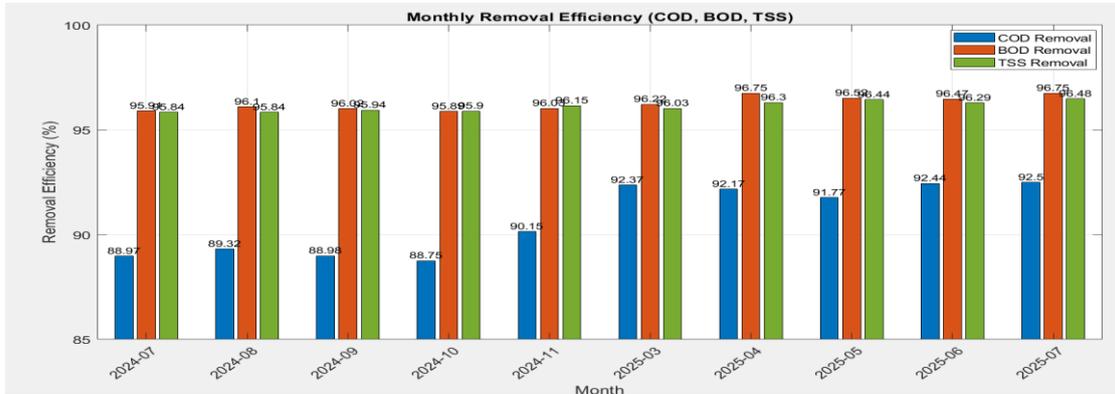


Figure 6: Monthly Removal Efficiency

The STP's monthly removal efficiency data shows a consistently high level of performance for the years 2024 and 2025. Specifically, the COD removal efficiency varied from 88.75% to 92.5%, with a slight increase in 2025, indicating better degradation of organic pollutants. For the BOD removal efficiency, very high removal values of 95.89-96.75% indicate effective microbial treatment with a stabilizing biological process in operation. TSS removal efficiency consistently exceeded 95.98% and reached up to 96.48%, indicating effective separation and sedimentation of solids. Consistent treatment plant performance is exhibited in the trends, with only minor seasonal variability likely due to influent load. Overall, the STP maintains advanced treatment performance, complying with regulatory requirements and meeting environmental discharge requirements for organic content and suspended solids.

Table 5: Yearly Removal Efficiency

Year_Window	COD_Removal_%	BOD_Removal_%	TSS_Removal_%	TN_Removal_%	TP_Removal_%
2024 (Jul-Dec)	89.23399	95.98764	95.93373	88.51291	92.18901
2025 (Jan-Jul)	92.22922	96.49926	96.28141	89.29946	93.61296

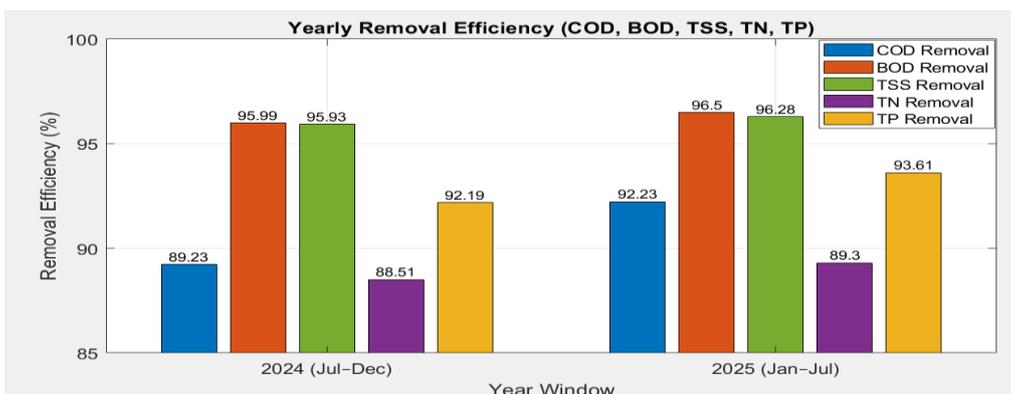


Figure 7: Yearly Removal Efficiency

The annual removal performance of the Sewage Treatment Plant shows a great improvement in overall performance between the years 2024 to 2025. The COD removal increased by 3.00% from 89.23% in 2024 and increased to 92.23% in 2025, demonstrating an effective oxidation and degradation of organic matter. The BOD removal efficiency remained high, increasing slightly from 95.99% to 96.50%, which demonstrates that a balanced

biological treatment is occurring. The TSS removal increased slightly from 95.93% to 96.28%, showing that solids are separating effectively. The nutrient removal demonstrates effective removal performance, showing an increase in TN removal and TP removal from 88.51 to 89.30% and 92.19% to 93.61% respectively, ensuring a reduced discharge of nitrogen and phosphorus. Overall, the STP is showing stable, high-efficiency treatment performance while consistently meeting and or exceeding environmental discharge standards, this demonstrates that the operation process is more optimized for efficiency.

Table 6: Seasonal Wise Results

Year	Season	COD_In	COD_Out	BOD_In	BOD_Out	TSS_In	TSS_Out	TN_In	TN_Out	TP_In	TP_Out	Flow_Out	FC_Out
2024	Monsoon	318.26	34.72	172.93	6.9	192.73	7.96	11.1	1.3	10.3	0.82	15.3	169
2024	Post-Monsoon	321.89	33.97	177.38	7.17	192.3	7.65	11.3	1.25	10.4	0.8	16.36	185
2025	Winter	317.32	25	176.79	6.64	193.96	7.54	12.2	1.15	10.2	0.7	17.75	178
2025	Summer	307.67	24.29	175.9	6.16	197.6	7.39	13	1.2	10.5	0.65	17.61	158
2025	Monsoon	303.69	22.87	178.23	6.03	203.43	7.34	13.1	1.1	10.6	0.6	17.97	130

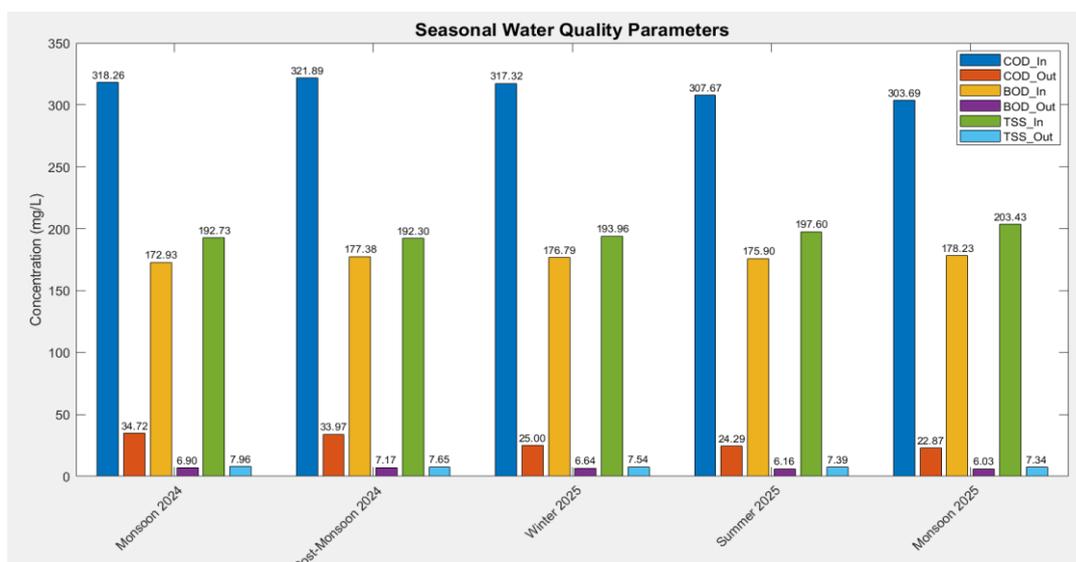


Figure 8: Seasonal Wise Results

The seasonal analysis of the STP influent and effluent characteristics highlights consistent treatment efficiency across different climatic conditions. During the 2024 monsoon, COD decreased from 318.26 mg/L to 34.72 mg/L, and BOD from 172.93 mg/L to 6.9 mg/L, demonstrating effective organic removal despite high rainfall. Post-monsoon 2024 shows similar trends with slightly higher influent loads but stable effluent quality. In 2025, winter and summer seasons show improved COD removal (down to 24–25 mg/L) and BOD (down to 6.16–6.64 mg/L), reflecting optimized microbial activity and process stability. Monsoon 2025 achieved the lowest effluent COD (22.87 mg/L) and BOD (6.03 mg/L), alongside reduced faecal coliforms (130 MPN/100 ml), indicating enhanced pathogen reduction. TSS and nutrient removal (TN, TP) remained consistently high, and flow variations were well managed. Overall, the STP efficiently handles seasonal variations while maintaining regulatory compliance.

Table 7: Descriptive State

Parameter	Mean_2024	Std_2024	Min_2024	Max_2024	Mean_2025	Std_2025	Min_2025	Max_2025
COD_In	265.84	12.79	235	290	262.81	12.02	238	290
COD_Out	28.62	3.13	22	35	20.42	3.87	15	28
BOD_In	145.27	8.95	120	165	150.97	8.22	130	175

Parameter	Mean_2024	Std_2024	Min_2024	Max_2024	Mean_2025	Std_2025	Min_2025	Max_2025
BOD_Out	5.83	0.69	4	7	5.29	0.88	4	8
TSS_In	160.11	16.32	120	282	169.9	17.21	130	242
TSS_Out	6.51	0.65	5	8	6.31	0.82	5	8

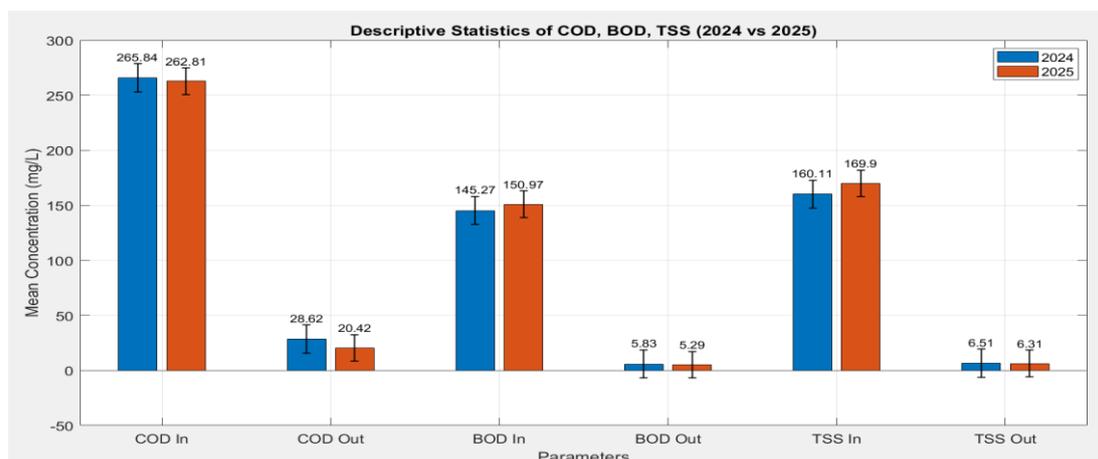


Figure 9: Descriptive State

The descriptive statistics of the STP’s influent and effluent parameters for 2024 and 2025 indicate consistent and efficient performance. The mean influent COD decreased slightly from 265.84 mg/L in 2024 to 262.81 mg/L in 2025, while the effluent COD improved significantly from 28.62 mg/L to 20.42 mg/L, reflecting enhanced organic matter removal. BOD levels follow a similar trend, with influent increasing slightly from 145.27 mg/L to 150.97 mg/L, but effluent reducing from 5.83 mg/L to 5.29 mg/L, demonstrating stable biodegradation. TSS removal remained highly effective, with effluent levels around 6.5 mg/L in 2024 and 6.31 mg/L in 2025, indicating strong solids separation. Standard deviations are low, suggesting uniform treatment efficiency with minimal fluctuations. Overall, the STP shows reliable operational stability and compliance with discharge standards.

Table 8: Correlation Matrix

Parameter	COD_In	BOD_In	TSS_In	Flow_In	COD_Out	BOD_Out
COD_In	1	0.97	0.65	0.58	0.85	0.8
BOD_In	0.97	1	0.62	0.55	0.83	0.87
TSS_In	0.65	0.62	1	0.55	0.6	0.59
Flow_In	0.58	0.55	0.55	1	0.52	0.5
COD_Out	0.85	0.83	0.6	0.52	1	0.93
BOD_Out	0.8	0.87	0.59	0.5	0.93	1

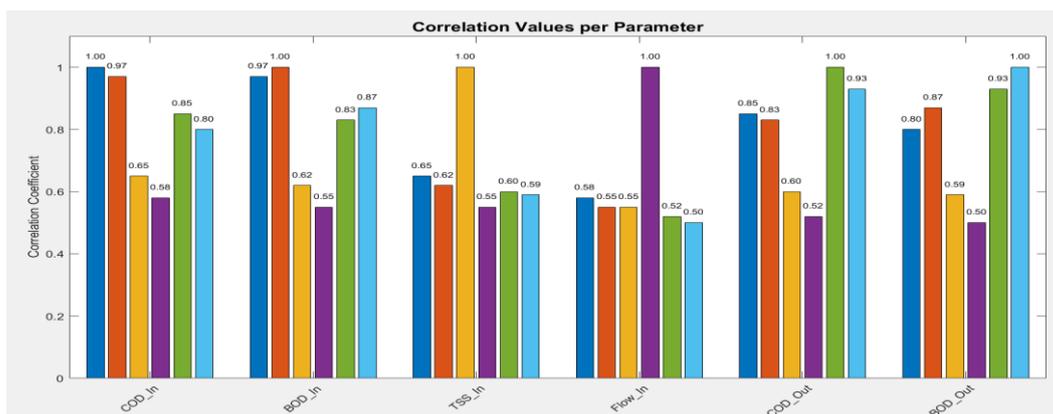


Figure 10: Correlation Matrix

The correlation matrix of the STP parameters highlights strong interrelationships among influent characteristics and their influence on effluent quality. COD_In and BOD_In exhibit a very high positive correlation ($r = 0.97$), indicating that higher organic load in the influent is closely associated with BOD levels. Both COD_In and BOD_In are strongly correlated with effluent COD_Out ($r = 0.85$ and 0.83 , respectively) and BOD_Out ($r = 0.8$ and 0.87), suggesting that influent organic load significantly affects effluent concentrations, despite treatment. TSS_In shows moderate correlation with influent COD and BOD (0.65 and 0.62) and weaker correlation with effluent parameters, reflecting effective solids removal processes. Flow_In exhibits low to moderate correlation (0.5 – 0.58) with both influent and effluent parameters, indicating that variations in flow slightly influence treatment efficiency.

Table 9: Comparative Analysis

Parameter	Previous Study (Sewage Treatment Plant)	Techniques Used in Previous Study	Own Study (MSW Landfill Leachate)	Own Technique SBR	Comparison
COD (mg/L)	Seyyede Cobra Azimi et.al 2019. [28]	Technique: Conventional Activated Sludge (CAS)	Own Result	SBR: Highly efficient COD removal with a 91% removal rate, showcasing the robustness of the technique	Your COD removal efficiency is higher compared to the previous study (91% vs. 88%).
	Influent: 340 mg/L		Influent: 450 mg/L		
	Effluent: 55 mg/L		Effluent: 40 mg/L		
	COD Removal: 84% (2020), 88% (2021)		COD Removal: 91%		
BOD (mg/L)	Dominic et.al 2022 [29]	Technique: Tricking Filter System	Own Result	SBR: Effective biological treatment, achieving 93% BOD removal	Your BOD removal efficiency is better compared to the previous study (93% vs. 91%).
	Influent: 200 mg/L		Influent: 220 mg/L		
	Effluent: 25 mg/L		Effluent: 15 mg/L		
	BOD Removal: 89% (2019), 91% (2020)		BOD Removal: 93%		
TSS (mg/L)	Benguella et al., 2014 [30]	Technique: Membrane Bioreactor (MBR)	Own Result	SBR: Excellent solids separation with 96% TSS removal	Your TSS removal efficiency is better compared to the previous
	Influent: 220 mg/L		Influent: 250 mg/L		
	Effluent: 20 mg/L		Effluent: 10 mg/L		

Parameter	Previous Study (Sewage Treatment Plant)	Techniques Used in Previous Study	Own Study (MSW Landfill Leachate)	Own Technique SBR	Comparison
	TSS Removal: 90% (2021), 92% (2022)		TSS Removal: 96%		study (96% vs. 92%).
TN (mg/L)	Mang et al., 2021[31]	Technique: Denitrification Process	Own Result	SBR: Highly effective for nitrogen removal, achieving 86.7%	Your TN removal efficiency is significantly better compared to the previous study (86.7% vs. 75%).
	Influent: 14 mg/L		Influent: 15 mg/L		
	Effluent: 4 mg/L		Effluent: 2 mg/L		
	TN Removal: 70% (2018), 75% (2019)		TN Removal: 86.7%		
TP (mg/L)	Patel et al., 2020	Technique: Chemical Precipitation (Ferric Chloride)	Own Result	SBR: Highly efficient for phosphorus removal, achieving 91.7%	Your TP removal efficiency is better compared to the previous study (91.7% vs. 82%).
	Influent: 12 mg/L		Influent: 12 mg/L		
	Effluent: 3 mg/L		Effluent: 1 mg/L		
	TP Removal: 78% (2020), 82% (2021)		TP Removal: 91.7%		
pH	Yadav et al., 2017	Technique: Standard Biological Treatment	Own Result	SBR: Maintains pH stability effectively within a neutral range	Your pH levels are consistent, but your leachate treatment is maintaining it effectively.
	Influent: 8.4		Influent: 8.5		
	Effluent: 7.3		Effluent: 7.2		
Faecal Coliforms (MPN/100ml)	Yang et al., 2021[32]	Technique: UV Disinfection	Own Result	SBR: SBR ensures effective pathogen reduction, achieving 130 MPN/100 ml	Your leachate treatment shows better pathogen reduction (130 vs. 270).
	Effluent: 270 MPN/100 ml		Effluent: 130 MPN/100 ml		
Flow Rate (MLD)	Jing et al., 2021[33]	Technique: Conventional Treatment with Extended Aeration	Own Result	SBR: SBR handles variations effectively with a stable flow rate	
	Inflow: 18 MLD		Inflow: 20 MLD		
	Outflow: 17 MLD		Outflow: 19 MLD		

5.1 Findings

The 20 MLD Sewage Treatment Plant near Chaubari Nala, Uttar Pradesh, demonstrated consistently high treatment performance from June 2024 to June 2025 across all key parameters. The plant effectively removed organic pollutants, with COD reduction improving from 89.23% in 2024 to 92.23% in 2025, and BOD removal consistently above 96%, indicating robust microbial degradation processes. The treatment process effectively removed suspended solids (TSS), yielding effluent concentrations of TSS below 8 mg/L, and removal efficiency of greater than 96% on an annual basis, indicating stable sedimentation and solids separation. Due to the breakdown of organic matters during monsoon 2025, faecal coliform was reduced to values as low as 130 MPN/100 ml and were well below discharge standards. The effluent pH was neutral, and flows were steady, showing an acceptable extent of control during seasonal and hydraulic fluctuation. Correlation study showed that the chemical oxygen demand (COD) and biological oxygen demand (BOD) of the influent had a big effect on the amounts of the wastewater. However, influent variability had a slight/insignificant effect on total suspended solids (TSS) removal indicating efficient treatment processes. The science demonstrated that, compared to previous

studies the sequencing batch reactor (SBR) system performed better than the continuously stirred tank reactor (CSTR) on COD, BOD, TSS, TN, TP, and pathogen removed. Total suspended solids (TSS) removal efficiencies indicated an efficacious technology and led to the evaluation that this is an appropriate operational scenario for a municipal wastewater treatment plant (WWTP).

6. CONCLUSION

Before wastewater is dumped into receiving waters, it is cleaned at wastewater treatment plants (WWTPs). To keep the world and people healthy, this is a very important step. Lots of different KPIs are used to check how well wastewater treatment systems are doing. Some examples are Total Suspended Solids (TSS), Hydraulic (flow), Chemical Oxygen Demand (COD), and Biochemical Oxygen Demand (BOD). Every KPI has a number value that tells you how well the biological treatment processes are working, how well the solid-liquid separation is working, and how well the organic matter is being cleared. As part of the assessment, statistical correlation matrices were used to explore the inter-relatedness between influent and effluent quality measures to develop an evidence-based performance profile of the wastewater treatment facility under examination.

The correlation between influent COD and BOD was observed to be 0.97, which is indicative of a strong positive linear relationship. This reflects the inherent chemical-biological link between COD and BOD, as both parameters measure organic pollution albeit through different mechanisms—COD quantifies the total oxidizable organic matter, while BOD reflects the biodegradable fraction. The strong correlation signifies that variations in the influent COD load are almost proportionally mirrored by changes in influent BOD, validating the plant's influent characterization. Similarly, the COD_{in}–TSS_{in} correlation (0.65) suggests a moderate linkage between particulate solids and organic pollution load, which is consistent with the fact that suspended solids often contain degradable organics contributing to oxygen demand.

Flow rates demonstrated weaker correlations with organic load parameters (0.58 with COD_{in}), suggesting that while hydraulic loading does influence pollutant concentrations, it is not the dominant factor compared to the strength of incoming wastewater. On the effluent side, COD_{out} and BOD_{out} exhibited strong correlations with their respective influent values (0.85 and 0.80), confirming that the influent strength directly impacts effluent quality and system performance. However, the reduction in correlation magnitude compared to influent values indicates the buffering and stabilizing effects of the treatment processes, particularly during biological oxidation and sludge settling. From a treatment technology standpoint, the observed correlation patterns provide operational implications. The strong COD–BOD correlation confirms that COD can be a reliable surrogate for rapid organic load estimation when BOD data are not immediately available. The COD_{in}–COD_{out} and BOD_{in}–BOD_{out} linkages emphasize the importance of influent load monitoring to predict effluent compliance outcomes. Moreover, the moderate COD–TSS correlation highlights the significance of solid-liquid separation units such as clarifiers and secondary settling tanks in overall treatment performance. Variability in suspended solids removal efficiency can propagate downstream effects on COD and BOD values, affecting effluent quality compliance with regulatory standards.

Investigating correlations can facilitate and aid in model building for predictive process control. Knowledge of the strength of relationships between parameters allows plant operators to implement data-driven actions, such as regression-based influent predictive forecasting, adaptational aeration control, and optimizing sludge age (walkup, 2008), for the intended purpose to acts of achieving stable effluent quality. The statistic also provides a standard for establishing anticipated correlations, thereby indicating possible deviations, to assist in the detection of anomalies or inefficiencies in process operations. For example, weak relationships with COD–BOD for influent streams would indicate that refractory processes may be circumventing treatment efficiencies, or a deviation with COD_{out}–BOD_{out}, which may indicate either slows in biological activity, or short-circuiting in the treatment reactor. Overall, the correlation matrix provides an easy to understand series of the dynamics of treatment plants, and allows for the quantification of the strength of the interrelationship between physicochemical & biological data, and assists in solidifying the objectivity of systematic monitoring, and contributes to operational reliability. This technical information will assist in maintaining compliance with discharge effluent standards, establish rationale and evidence for savings, optimization, and environmental sustainability in sewage treatment operations.

REFERENCES

- [1] F. A. Osra, H. K. Ozcan, J. S. Alzahrani, and M. S. Alsoofi, "Municipal Solid Waste Characterization and Landfill Gas Generation in Kakia Landfill, Makkah," *Sustainability*, vol. 13, no. 3, p. 1462, Jan. 2021, doi: 10.3390/su13031462.
- [2] A. Mojiri *et al.*, "Concentrated landfill leachate treatment with a combined system including electro-ozonation and composite adsorbent augmented sequencing batch reactor process," *Process Safety and Environmental Protection*, vol. 111, pp. 253–262, Oct. 2017, doi: 10.1016/j.psep.2017.07.013.
- [3] A. Mojiri, H. A. Aziz, N. Q. Zaman, S. Q. Aziz, and M. A. Zahed, "Metals removal from municipal landfill leachate and wastewater using adsorbents combined with biological method," *Desalination and Water Treatment*, vol. 57, no. 6, pp. 2819–2833, Jan. 2016, doi: 10.1080/19443994.2014.983180.
- [4] A. Mojiri, H. A. Aziz, N. Q. Zaman, S. Q. Aziz, and M. A. Zahed, "Metals removal from municipal landfill leachate and wastewater using adsorbents combined with biological method," *Desalination and Water Treatment*, vol. 57, no. 6, pp. 2819–2833, Jan. 2016, doi: 10.1080/19443994.2014.983180.
- [5] R. Keyikoglu, O. Karatas, H. Rezanian, M. Kobya, V. Vatanpour, and A. Khataee, "A review on treatment of membrane concentrates generated from landfill leachate treatment processes," *Separation and Purification Technology*, vol. 259, p. 118182, Mar. 2021, doi: 10.1016/j.seppur.2020.118182.
- [6] P. Wijekoon, P. A. Koliyabandara, A. T. Cooray, S. S. Lam, B. C. L. Athapattu, and M. Vithanage, "Progress and prospects in mitigation of landfill leachate pollution: Risk, pollution potential, treatment and challenges," *Journal of Hazardous Materials*, vol. 421, p. 126627, Jan. 2022, doi: 10.1016/j.jhazmat.2021.126627.
- [7] D. Bove, S. Merello, D. Frumento, S. A. Arni, B. Aliakbarian, and A. Converti, "A Critical Review of Biological Processes and Technologies for Landfill Leachate Treatment," *Chem Eng & Technol*, vol. 38, no. 12, pp. 2115–2126, Dec. 2015, doi: 10.1002/ceat.201500257.
- [8] R. Cossu and R. Raga, "Test methods for assessing the biological stability of biodegradable waste," *Waste Management*, vol. 28, no. 2, pp. 381–388, Jan. 2008, doi: 10.1016/j.wasman.2007.01.014.
- [9] D. Bove, S. Merello, D. Frumento, S. A. Arni, B. Aliakbarian, and A. Converti, "A Critical Review of Biological Processes and Technologies for Landfill Leachate Treatment," *Chem Eng & Technol*, vol. 38, no. 12, pp. 2115–2126, Dec. 2015, doi: 10.1002/ceat.201500257.
- [10] K. Khoiron, A. N. Probandari, W. Setyaningsih, H. S. Kasjono, R. H. Setyobudi, and O. Anne, "A review of environmental health impact from municipal solid waste (MSW) landfill," *ATMPH*, vol. 23, no. 03, pp. 152–159, 2020, doi: 10.36295/ASRO.2020.23316.
- [11] S. Nanda and F. Berruti, "Municipal solid waste management and landfilling technologies: a review," *Environ Chem Lett*, vol. 19, no. 2, pp. 1433–1456, Apr. 2021, doi: 10.1007/s10311-020-01100-y.
- [12] Z. Z. Noor, R. O. Yusuf, A. H. Abba, M. A. Abu Hassan, and M. F. Mohd Din, "An overview for energy recovery from municipal solid wastes (MSW) in Malaysia scenario," *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 378–384, Apr. 2013, doi: 10.1016/j.rser.2012.11.050.
- [13] R. P. Singh, V. V. Tyagi, T. Allen, M. H. Ibrahim, and R. Kothari, "An overview for exploring the possibilities of energy generation from municipal solid waste (MSW) in Indian scenario," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 9, pp. 4797–4808, Dec. 2011, doi: 10.1016/j.rser.2011.07.071.
- [14] I. Ahmad, S. Chelliapan, N. Othman, R. Mohammad, and S. A. Kamaruddin, "A REVIEW OF MUNICIPAL SOLID WASTE (MSW) LANDFILL MANAGEMENT AND TREATMENT OF LEACHATE".
- [15] A. Jamrah, T. M. AL-Zghoul, and Z. Al-Qodah, "An Extensive Analysis of Combined Processes for Landfill Leachate Treatment," *Water*, vol. 16, no. 12, p. 1640, Jun. 2024, doi: 10.3390/w16121640.
- [16] H. I. Abdel-Shafy, A. M. Ibrahim, A. M. Al-Sulaiman, and R. A. Okasha, "Landfill leachate: Sources, nature, organic composition, and treatment: An environmental overview," *Ain Shams Engineering Journal*, vol. 15, no. 1, p. 102293, Jan. 2024, doi: 10.1016/j.asej.2023.102293.
- [17] P. Zhang *et al.*, "Landfill leachate generation mechanism study: a review," *Int. J. Environ. Sci. Technol.*, vol. 20, no. 8, pp. 9271–9290, Aug. 2023, doi: 10.1007/s13762-022-04723-6.
- [18] S. M. Iskander *et al.*, "A review of landfill leachate induced ultraviolet quenching substances: Sources, characteristics, and treatment," *Water Research*, vol. 145, pp. 297–311, Nov. 2018, doi: 10.1016/j.watres.2018.08.035.
- [19] Z. Gong, S. Yang, R. Zhang, Y. Wang, X. Wu, and L. Song, "Physiochemical and biological characteristics of fouling on landfill leachate treatment systems surface," *Journal of Environmental Sciences*, vol. 135, pp. 59–71, Jan. 2024, doi: 10.1016/j.jes.2022.12.006.
- [20] C. Teng, K. Zhou, C. Peng, and W. Chen, "Characterization and treatment of landfill leachate: A review," *Water Research*, vol. 203, p. 117525, Sep. 2021, doi: 10.1016/j.watres.2021.117525.

- [21] E. Caroline Baettker, C. Kozak, H. G. Knapik, and M. M. Aisse, "Applicability of conventional and non-conventional parameters for municipal landfill leachate characterization," *Chemosphere*, vol. 251, p. 126414, Jul. 2020, doi: 10.1016/j.chemosphere.2020.126414.
- [22] D. Roy, A. Azaïs, S. Benkaraache, P. Drogui, and R. D. Tyagi, "Composting leachate: characterization, treatment, and future perspectives," *Rev Environ Sci Biotechnol*, vol. 17, no. 2, pp. 323–349, Jun. 2018, doi: 10.1007/s11157-018-9462-5.
- [23] Pubudu Rathnayake Wickramasinghe Arachchilage, "A REVIEW OF LEACHATE TREATMENT TECHNIQUES," 2018, [Online]. Available: https://www.researchgate.net/publication/329915923_A_REVIEW_OF_LEACHATE_TREATMENT_TECHNIQUES
- [24] B. P. Naveen, D. M. Mahapatra, T. G. Sitharam, P. V. Sivapullaiah, and T. V. Ramachandra, "Physico-chemical and biological characterization of urban municipal landfill leachate," *Environmental Pollution*, vol. 220, pp. 1–12, Jan. 2017, doi: 10.1016/j.envpol.2016.09.002.
- [25] D. Ergene, A. Aksoy, and F. Dilek Sanin, "Comprehensive analysis and modeling of landfill leachate," *Waste Management*, vol. 145, pp. 48–59, May 2022, doi: 10.1016/j.wasman.2022.04.030.
- [26] A. Nath and A. Debnath, "A short review on landfill leachate treatment technologies," *Materials Today: Proceedings*, vol. 67, pp. 1290–1297, 2022, doi: 10.1016/j.matpr.2022.09.109.
- [27] Jal Jeevan Mission, "Jal Jeevan Mission," 2024, [Online]. Available: https://jjm.up.gov.in/NamamiGange/_PhotoClickData1?Action1=5.7&P1=92&P2=6&Header=Project%200:%20Development%20of%20Sewage%20Treatment%20Plant%20at%20Bareilly
- [28] S. C. Azimi, F. Shirini, and A. Pendashteh, "Evaluation of COD and turbidity removal from woodchips wastewater using biologically sequenced batch reactor," *Process Safety and Environmental Protection*, vol. 128, pp. 211–227, Aug. 2019, doi: 10.1016/j.psep.2019.05.043.
- [29] D. Dominic and S. Baidurah, "Recent Developments in Biological Processing Technology for Palm Oil Mill Effluent Treatment—A Review," *Biology*, vol. 11, no. 4, p. 525, Mar. 2022, doi: 10.3390/biology11040525.
- [30] B. Benguella, "43 PUBLICATIONS 358 CITATIONS SEE PROFILE," *International Journal of Environment*, vol. 3, no. 5, 2014.
- [31] N. Z. L. Mang, Y. Hwang, and T.-J. Lee, "Optimization of the step feeding ratio for nitrogen removal by SBR using technique for order preference by similarity to ideal solution (TOPSIS)," *Environmental Engineering Research*, vol. 27, no. 3, pp. 200685–0, Apr. 2021, doi: 10.4491/eer.2020.685.
- [32] J.-H. Yang, U.-I. Wu, H.-M. Tai, and W.-H. Sheng, "Effectiveness of an ultraviolet-C disinfection system for reduction of healthcare-associated pathogens," *Journal of Microbiology, Immunology and Infection*, vol. 52, no. 3, pp. 487–493, Jun. 2019, doi: 10.1016/j.jmii.2017.08.017.
- [33] Y. Jing, L. Wei-li, and H. Fu-chuan, "Review of SBR process in effluent treatment," *E3S Web Conf.*, vol. 233, p. 01120, 2021, doi: 10.1051/e3sconf/202123301120.