STUDY OF SIMULATION-BASED MODELING OF A PLUG FLOW TANK AND A MEMBRANE BIOREACTOR UNDER STOCHASTIC INFLUENT CONDITIONS

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ABSTRACT

There is a need to choose the right design of wastewater treatment facilities to achieve optimal performance and reliability at minimum cost. In this paper, a comparison of two kinds of Activated Sludge Processes (ASP), PFT and MBR, is conducted based on the simulation model GPS-X, in which the influent data are stochastically generated. It was coded in Python and produced influent scenarios (e.g., flow, COD, BOD, TSS, nutrients, and physicochemical parameters) using real municipal sewage with different ranges and degrees of variability. The process performance evaluation revealed that the two systems are capable of attaining similar maximum and mean removal efficiencies (COD 59%, BOD 56%, TSS 95%, overall 68.5%), but the stability of the two systems varies. The PFT was also more diverse, especially in the removal of COD and TSS. On the other hand, the MBR had much smaller distributions for all the metrics. Despite interdependencies between COD, BOD, and the overall efficiency when correlated with each other, the removal of TSS was quite independent of the other responses. Although the statistical tests did not produce any significant differences in the means of the systems, the lowest variance with the highest consistency, reflecting superior operational reliability, belonged to the MBR. These results support the idea that peak efficiency is not the only parameter when choosing a system, and that consistency in the system selection process under varying influent conditions should play a significant role. PFT is more appropriate for stable and cost-efficient projects, whereas MBR is typically used in facilities requiring greater effluent control, higher reliability, or reuse of treated water. By integrating the two approaches into one model, engineers and policymakers can have a clear and data-driven way to evaluate options and determine which wastewater treatment technology is most rational for specific needs.

Keywords: *Wastewater Treatment, Activated Sludge Process (ASP), Plug Flow Tank (PFT), Membrane Bioreactor (MBR), GPS-X*

1. INTRODUCTION

A good and efficient wastewater treatment plant (WWTP) is a major element in protecting human health and healthy aquatic environments. Of the various treatment methods in existence, the activated sludge process has been the most popular. It is approximated that the method is used in more than 80 percent of the wastewater treatment plants in the world today because it is not only very effective in the removal of contaminants but also flexible enough to treat different wastes (Fan et al., 2023). Engineers have over the years developed several types of designs that improve the performance and cost efficiency of the activated sludge process, from the initial Plug Flow Tank (PFT) through to the present day Membrane Bioreactor (MBR). These solutions allow more effective treatment outcomes, greater reliability, and potential reductions in cost. However, a significant problem in comparing such systems is the absence of complete and dependable full-scale operating data, especially for specific regions. The majority of plants use generic monitoring and reporting templates that in most cases lack enough detail for significant performance analysis. This kind of inadequate data makes it more difficult to make evidence-based decisions when designing new facilities or remodeling existing ones (Katam & Bhattacharyya, 2021). This data availability gap has made simulation-based modeling an important tool for environmental engineers. Software like the GPS-X platform allows for high-level modeling of complex biochemical processes under controlled and reproducible conditions to gain insights that might otherwise require extensive field experiments. However, the reliability of such simulations is fundamentally dependent on the quality and representativeness of the input data. A major issue is the need for a representative dataset that accurately captures the inherent variability in municipal wastewater, as simulation results are highly sensitive to input conditions (Odeibat et al., 2024). Recent work by Martin et al. (2023) highlights the value of stochastic modeling for introducing realistic variability in influent parameters (such as flow and chemical composition) to better represent real sewer system behavior, an approach applicable to treatment process modeling. Therefore, to address the problem of inconsistent real-world data for comparative analysis, this study employs a combined computational method. We developed a stochastic modeling framework in Python to generate realistic, variable influent patterns for flow, chemical oxygen demand (COD), nitrogen forms, and phosphorus. This synthetic data, designed to reflect the operation of a real municipal sewer system, was then used as input for simulations on the GPS-X platform.

The objective of this study is to explicitly compare the treatment performance and operational behavior of a conventional Plug Flow Tank (PFT) system with a Membrane Bioreactor (MBR) under conditions of realistic influent variability. Using the synthetic influent data, we simulated both systems and analyzed the resulting effluent quality. The aim is to understand how each reactor configuration affects the stability of effluent quality and to arrive at a practical, evidence-based recommendation that engineers can use when selecting a system based on specific plant requirements. This technique enables a controlled and sensible comparison, free from the inconsistencies and noise typical of incomplete operational datasets.

2. METHODOLOGY

In this study, simulations were done to compare two Activated Sludge Process (ASP) systems, which included a traditional Plug Flow Tank (PFT) and Membrane Bioreactor (MBR). We desired to come up with an objective and an effective way of quantifying the performance of each system to control the natural variability and ever-changing conditions of the real wastewater, and yet make the process sound scientifically. This was divided into four big steps that involved the formulation of a variable influent profile, model loading and calibration, and simulation.

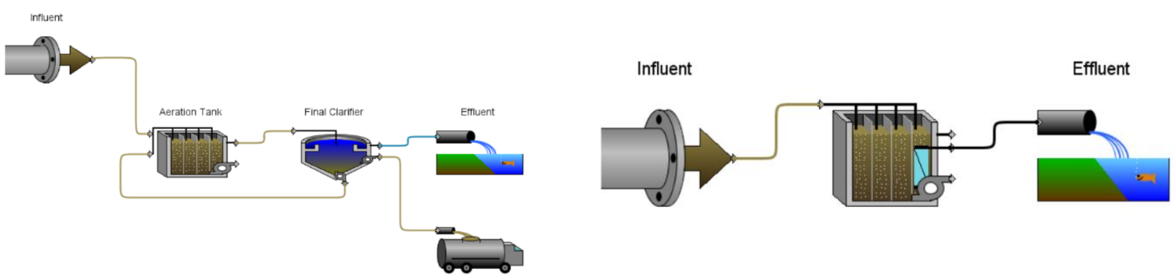
The first phase was the establishment of a range of but real synthetic wastewater properties. A single Python code was created to create ten influential scenarios and the limits of the mean, the standard deviation, and upper and lower limits of each scenario were created probabilistically. We also modeled certain important parameters of sewers with the help of the statistical distributions which are applied to model the variance in the collection system. An example was the flow rate in which it was designed to replicate variation by time at the daily and seasonal levels of time. The interval was 40000-60000 m3/d was needed and hence we used a log-normal distribution restricted to these values. This is the rate of flow of a huge wastewater treatment plant serving a population of nearly 400,000 people where the per-capita consumption of water is 140 litres per person per day of the world. This size is directly associated with bigger projects which have been implemented in the recent past under the umbrella project of the Chattogram Sewerage System Development Master Plan such as the Kalurghat plant with a nominal capacity of 60,000 m3/day, or the Halishahar plant with a nominal capacity of 50,000 m3/day (Chowdhury, 2025).
The carbonaceous biochemical oxygen demand (cBOD5) was measured according to a five-day log-norm distribution to reflect the random changes in the municipal wastewater, truncated to the realistic level of 100 to 500 mg/L (Salinas, 2024). This is one of the most popular methods of probabilistic treatment, taking into account the change in the representation of the wastewater (Partani et al., 2025). The cBOD5 was then converted into the total COD concentrations with varying conversion factor of 1.8 to 2.4. The range produces BOD5 /COD ratios of around 0.56 -0.42 that can be compared to ratios that are commonly found in the municipal wastewater which is easily biodegradable (Wei et al.,2023). This fact is significant because the quantity and the biodegradability of organic matter in the influent changes naturally with time and place. The ammonia-N concentrations were generated as a truncated set of the log-normal distributions which are often encountered in the environmental studies, which are 15-60 mg/L, or other close values (Limpert et al., 2001). We also used a value of between 0.60 and 0.70 to divide ammonia value to get Total Kjeldahl Nitrogen (TKN). Since the ammonia content in the municipal wastewater in most instances is between 60-70% of the total TKN, this process ensures a realistic proportion of inorganic (ammonia) to organic forms of nitrogen (Henze et al., 2008). A range of 2-20 mg/L was used in the case of Total Phosphorus (TP) where gamma distribution was applied. The common skewed right distribution is employed in describing the skewed right distribution of phosphorus data which is mainly low with a few spikes due to occasional sources of phosphorus like detergents, stormwater inflow or industrial discharges (Gernaey et al., 2011; Riechel et al., 2016).
Other vital physicochemical parameters were also factored in so as to fill in the model. With pH, we began with the perfect pH but we changed the model to a normal distribution with the mean of 7.2, standard deviation of 0.3 and a range between 6.5 and 8.0. This is typical of regular municipal wastewater which is usually close to neutral with some variation caused by the contribution of industrial wastes or microbial processes (Metcalf & Eddy et al., 2014). Dissolved Oxygen (DO) values were determined using a standard conditional normal distribution and the mean was 2.0 or 2.5mg/L with a standard deviation of 0.3 to 0.4 which fell within the 0.5 to 6.0mg/L range. Such situations concentrate the expected variability on a daily and seasonal basis of a tropical climate whereby, DO is expected to decline on the warmer days or night due to reduced re-aeration and further microbial respiration (Olsson, 2012). There were also conditional normal distributions with a mean temperature of 25 °C and a standard deviation of 2-3°C and a range of 10-35°C to model temperature. Such a set up signifies the variations between hot and cooler seasons of pre-monsoon seasons and this is important because temperature directly relates to the rate of reaction of biological treatment systems (Henze et al., 2008). We then tabulated all ten sets of influence put in a single table and generated separate CSV files of each set of ten parameters. This framework allowed us to have good situations and gave a repeatable and predictable framework of how to repeat the study.

Table 1: Stochastic influent wastewater characteristics used for simulation.

Q(m^3/d)	COD (mg/L)	TKN (mg/L)	TP (mg/L)	pH	DO (mg/L)	T(°C)	Ammonia nitrogen (mg/L)

56642	310.13	55.3	20	7.43	2.36	24.09	19.21
45165	343.04	22.11	8.78	6.77	1.54	23.75	22.62
52469	182.06	52.55	9.76	6.61	2.3	23.34	27.34
55356	188.46	63.51	4.01	7.11	2.36	22.63	37.82
55506	242.56	52.83	2	7.45	2.03	22.4	54.5
46571	272.29	69.3	5.36	7.35	2.29	22.34	36.62
42518	225.12	44.34	20	7.25	1.92	22.95	35.92
51080	325.62	47.86	18.1	7.43	2.92	20.79	34.33
53367	254.6	41.58	3.19	7.34	1.69	24.03	30.07
41311	302.07	75.99	12.18	7.29	2.3	23.46	16.84

The second phase was the biological treatment models were set on the GPS-X simulation platform. In order to describe the biological mechanisms in the two systems we chose the Activated Sludge Model No. 3 (ASM3) because the ASM3 is able to model the two processes of organic matter removal and storage. Plug Flow Tank was modeled as a sequence of complete mixed aerobic reactors and a clarifier that followed and Membrane Bioreactor was characterized as a sequence of complete mixed aerobic reactor followed by a membrane filtration system under which a perfect solid-liquid separation was used. This "perfect solid-liquid separation" is a simplifying assumption used to isolate and compare the core biological and hydraulic performance of the two reactor configurations. In this model, membrane fouling dynamics and their associated effects on permeability and energy consumption are not simulated. This approach is justified for the study's goal of a controlled, baseline performance comparison under identical biochemical and influent conditions. And this study is only focusing on the inherent treatment potential of each system's design before factoring in site-specific fouling management. Figure 1 illustrates the schematic view of these two systems in a configured form. The variable was the effect of configuration differences where the two systems were operated at a similar sludge retention time and biomass concentration.
In the third phase, the ten influent conditions were simulated under each system configuration in GPS-X at steady state and the results on the effluent quality (concentrations of COD, BOD, TSS, TKN and TP) and removability efficiencies were acquired and computed depending on the resulted effluent quality concentrations. In the last stage, we conducted extensive data processing in Python that consisted of descriptive statistics, correlation analysis, independent samples t-test hypothesis test, and more sophisticated graphics boxplots, histograms, and scatter plots to analyze the relative system performance and reliability to the generated influent conditions.



(a) *(b)*

Figure 1: GPS-X model configuration for the evaluated activated sludge systems: (a) Membrane Bioreactor (MBR) configuration (b) Conventional Plug Flow Tank configuration

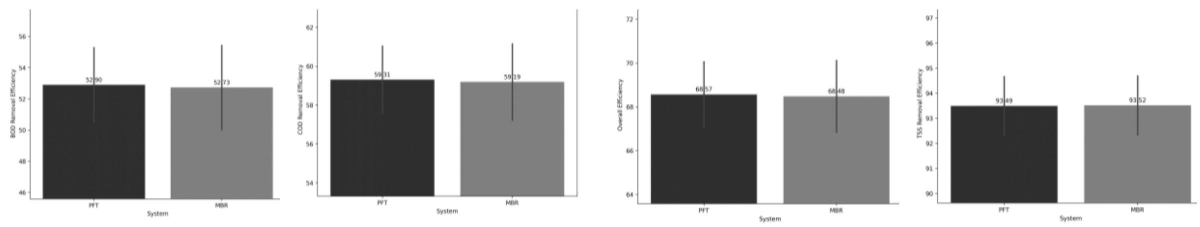
3. RESULTS AND DISCUSSION

The performance of two treatment systems in this case study, a Plug Flow Tank (PFT) and a Membrane bioreactor (MBR) will be compared in terms of steady-state performance using GPS-X simulation data. Chemical Oxygen Demand (COD) removal, Biological Oxygen Demand (BOD) removal, Total Suspended Solids (TSS) removal and overall treatment efficiency were the key performance indicators used to measure their effectiveness and reliability.

Efficiency of the organic matter removal was measured by the amount of organic matter extracted out of the soil compared to the amount of water that was used in the extraction process.

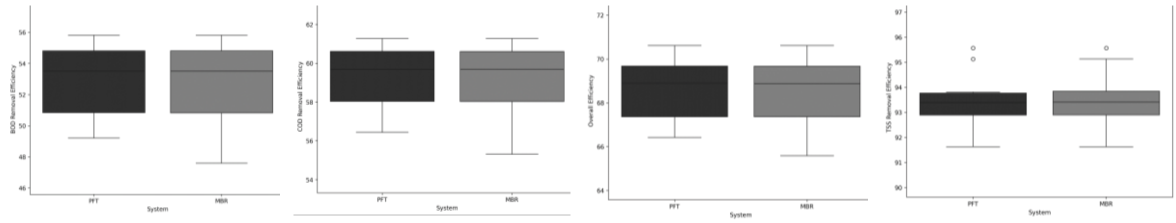
3.1 Organic Matter Removal Efficiency

The Overall Efficiency is a composite metric calculated as the average of the COD, BOD, and TSS removal efficiencies. This provides a single, aggregated indicator of general treatment performance for comparative purposes. The bar graphs (Figure 2a, 2b) and box plots (Figure 3a, 3b) show that the two systems had similar maximum organic matter removal efficiencies with the highest overall efficiencies of 59% with COD and 56% with BOD. However, the histogram distributions (Figure 4a, 4b) and box plots show that the difference in the operational stability is significant. The MBR generated data points which were more closely clustering and greater at higher levels of efficiency and the PFT had more widely spread values (COD: 54-59%; BOD: 46-56%). Generally, the simulations demonstrate that the similarity in the maximum removal performance of the two designs was nearly the same, with average COD and BOD5 removal efficiencies of about 59% and 56%, respectively. It is the separateness of consistency. The Plug Flow Tank had much larger oscillations in overall performance with the Membrane Bioreactor producing considerably more consistent results. This stability of the MBR is largely explained by the ability of the membrane to isolate the solids retention time (SRT) and hydraulic retention time (HRT), which is one of the major advantages ensuring the rise in the concentration of mixed liquor suspended solids (MLSS) and the consistency of the quality of the effluent (Le-Clech et al., 2003). Remarkably, this separation allows operating below the critical flux, which is likely to cause the severe contamination of membranes and can help avoid the rapid deterioration of performance when the transmembrane pressure (TMP) suddenly rises (Meng et al., 2009). The aeration also applies hydrodynamic scouring to control the fouling of membranes and reduce the deposition of foulants on the membrane surface (Le-Clech et al., 2003). In comparison, the PFT is based on gravitational settling, and thus it is prone to hydraulic disturbances and changes in sludge settleability. Sludge characteristics such as floc structure and extracellular polymeric substances (EPS) and soluble microbial products (SMP) availability play a major role in its functionality. These are the compounds that are known to make bad settling behavior and it is the major factors that cause bad quality of effluent (Le-Clech et al., 2003).



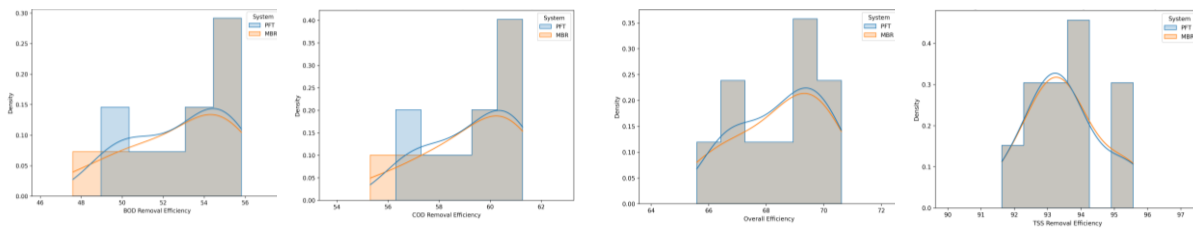
(a) *(b)* *(c)* *(d)*

Figure 2. Bar Chart Comparison of Removal Efficiencies Between PFT and MBR Systems (a) BOD Removal Efficiency (b) COD Removal Efficiency (c) Overall Efficiency (d) TSS Removal Efficiency



(a) *(b)* *(c)* *(d)*

Figure 3. Box plot Comparison of Removal Efficiencies Between PFT and MBR Systems (a) BOD Removal Efficiency (b) COD Removal Efficiency (c) Overall Efficiency (d) TSS Removal Efficiency



(a) *(b)* *(c)* *(d)*

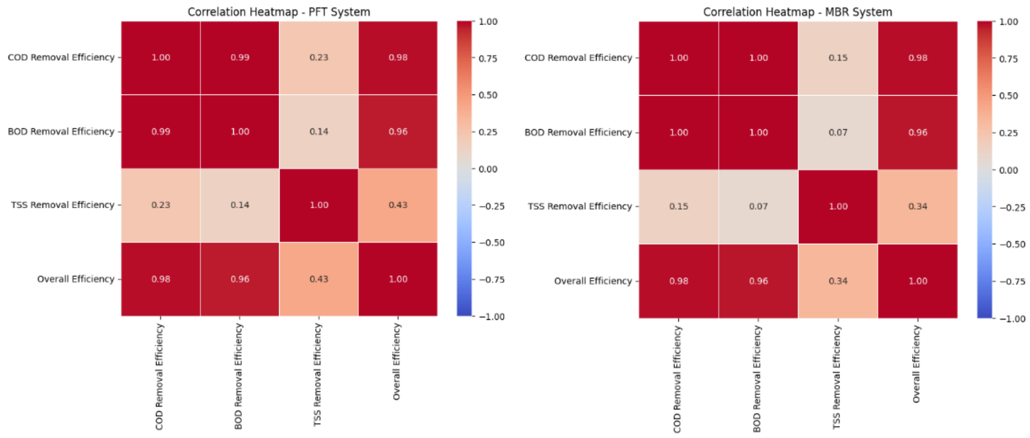
Figure 4. Histogram Comparison of Removal Efficiencies Between PFT and MBR Systems (a) BOD Removal Efficiency (b) COD Removal Efficiency (c) Overall Efficiency (d) TSS Removal Efficiency

3.2 Removal and Performance of Solids in General

In total suspended solids (TSS), the two treatment systems were highly efficient in their removal with the two having a removal efficiency of more than 94. It agrees with the findings made by Sasani et al. (2021), who achieved almost total TSS removal (around 99%) in a Membrane Bioreactor (MBR) and a Conventional Activated Sludge/Ultrafiltration (CAS/UF) system and explained their intensive performance by high solid-liquid separation performance of the membranes (Sasani & Ghasemi, 2021). However, our results present an additional data on the stability of the processes. As the clarifier acted and the sludge settled, the MBR has continually removed TSS at 94-96% and PFT was more variable (91-95%). The overall evaluation of the treatment performance, which is a compilation of a number of indicators (Figures 2c, 3c, and 4c) also shows this inclination. The distributions of performance of the two configurations were not equal even though the two configurations obtained almost equal peak efficiencies of about 68.5 % and had close median values (PFT: 68.57 %; MBR: 68.48 %) displaying similar expected capacity. The MBR gave more homogenous and predictive set of results but the PFT occasionally dropped to 64%. These findings imply that separation by the membrane in the MBR causes the solids to be separated, hence giving a more stable operation. Practically, this enhanced uniformity makes the facilities that have adopted MBR systems to meet regulatory discharge requirements with fewer swings.

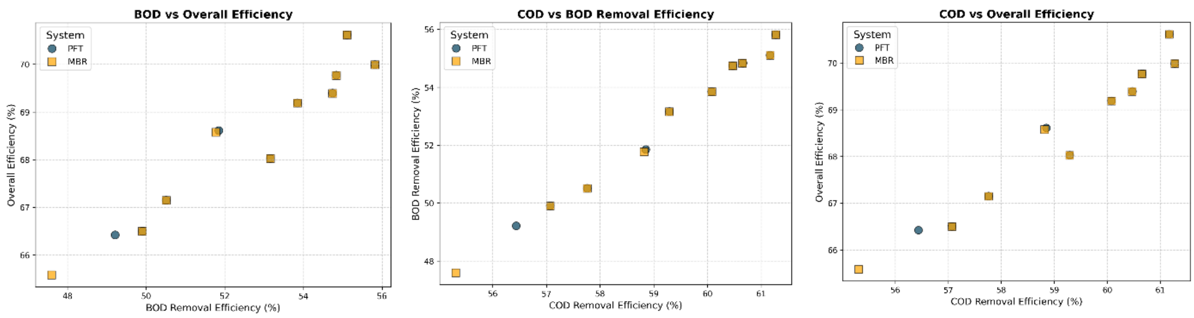
3.3 Correlation and Inter-parameter Analysis

Figure 5 presents correlation heat map of the different performance indicators. There is a very strong relationship between the efficiencies of COD and BOD removal (r = 0.99). The two measures also have a significant correlation with the Overall Efficiency with COD and BOD at r = 0.98 and r = 0.96 respectively. This demonstrates that the general performance of the treatment of wastewater is primarily attributed to the elimination of the organic material. However, TSS removal does not have much or no relation with organic removal. It is also heavily correlated with COD (r = 0.18) and BOD (r = 0.10), which is very low indicating that the solid-liquid separation occurs most of the time without the interference of organic pollutants degradation that is carried out by the biology. This is informed by the fact that the correlation between TSS and Overall Efficiency (r = 0.38) is low meaning that TSS removal is not the most relevant consideration to the performance but it has some influence. The correlations are also illustrated in Figure 6 scatter plots. Figure 6b indicates that the correlation between COD and BOD is nearly linear (r = 0.99) with all the points being clustered around the trend line. This means that the proportion of the total organic matter to the biodegradable part of the effluent is also fixed, and suggests that the biochemical basis of organic degradation in the two systems is fixed. The fact that COD removal and Overall Efficiency are strongly related (r = 0.98) is also proved in Figure 6c. The data information is highly concentrated in a single direction forming a clear upward trend that demonstrates that the more COD is eliminated, the more the entire treatment effectiveness will be achieved. On the other hand, the correlation between TSS removal and Overall Efficiency (r = 0.38) in Figure 6f is weak to moderate with the values being very scattered. Although the fact that the higher the TSS is removed, the higher some improvement of the overall score is, it is clear that this is not the defining factor and proves the idea that solids removal does increase performance, but not determine it.

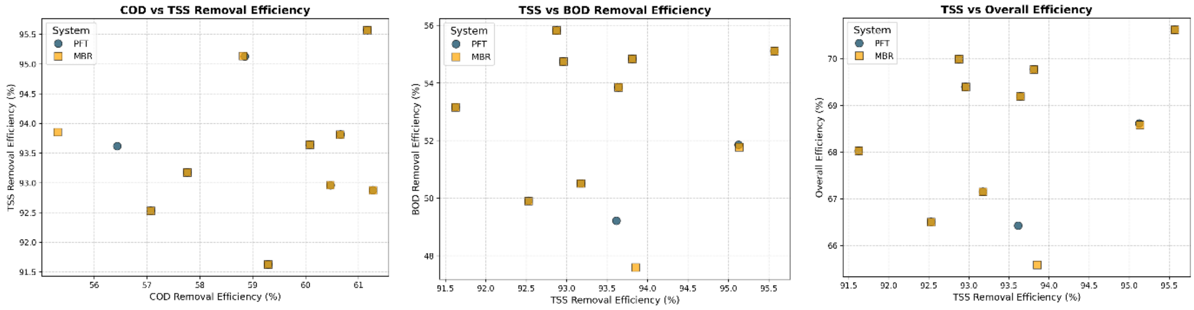


(a) *(b)*

Figure 5: Correlation Heatmap: *(a)* Plug Flow Tank *(b)* Membrane Bioreactor (MBR)



(a) *(b)* *(c)*



(d) *(e)* *(f)*

Figure 6. Correlation of Removal Efficiencies and Overall Efficiency in Wastewater Treatment Systems (a) BOD vs Overall Efficiency (b) COD vs BOD Removal Efficiency (c) COD vs Overall Efficiency (d) COD vs TSS Removal Efficiency (e) TSS vs BOD Removal Efficiency (f) TSS vs Overall Efficiency

The reason is that the measure of the Overall Efficiency is highly affected by the organic (COD/BOD) removal that is not dependent on physical solids separation at all. The relationship between TSS vs. BOD Removal (Figure 6e) and COD removal vs. TSS Removal (Figure 6d) are very weak ($r = 0.10$ and $r = 0.18$, respectively) and the variables are intensely dispersed without any recognisable trend. This is graphically confirmed to say that biological oxidation efficiency (BOD/COD removal) can be disaggregated of physical solid-liquid separation efficiency (TSS removal). A system may be highly organic removed yet only mediocre solids removed (some PFT data points), and the reverse may be true; may be near-perfect TSS removed yet only moderate organic removal.

The results also indicate that the process optimization strategy, such as SRT optimization or dissolved oxygen control, should be geared towards positively affecting the performance of the entire treatment process, but not solids management. The removal of solids can be optimized independently often; this is typical of MBR retrofit projects when the membrane is introduced to augment TSS removal without disturbing the biological process. The fact that the MBR data points at the maximum TSS removal in all the relevant and applicable figures are indicative of its special ability to consistently achieve maximum solids removal, despite its ability to remove soluble organic matter.

3.4 Statistical Significance of Differences in performance

Independent samples t-tests were used to compare the mean removal efficiencies and determine whether the differences that were observed between the two systems were statistically significant. The p-value of COD, BOD, TSS, and the total efficiency as presented in Table 2 were greater than the recommended p-value of 0.05. This confirms the fact that the treatment of the PFT and MBR systems do not have a statistically different average performance.

Table 2: Results of independent samples t-test comparing mean removal efficiencies between PFT and MBR systems.

Performance Indicator	t-statistic	p-value
COD Removal Efficiency	0.143	0.888
BOD Removal Efficiency	0.150	0.882
TSS Removal Efficiency	-0.047	0.963
Overall Efficiency	0.126	0.901

This statistical conclusion must be read along with the analysis of distribution. These differ not in the means, but differ in the variances. The t-test only gives a comparison of the difference in the means and not any information about the stability and variance of the underlying data. Therefore, the average level of treatment they achieve is not the primary disparity in their operational characteristics but the degree to which they have been achieved reliably. The invented MBR with the filtration unit of membranes considerably reduces the fluctuation of performance, contributing to the more predictable and stable operation.

3.5 Synthesis and Practical Implications

By comparison, we can comprehend that both PFT and MBR systems are capable of high performance in regard to treatment with respect to organic matter and solids removal and general treatment purposes. However, when the box plots, bar charts and histograms are analyzed more closely, one will see that the greatest difference is as obvious as possible: the MBR is much more uniform in its results. Such difference plays a big role in decision-making process concerning the technology. Even in a scenario where the facility values the simplicity of the operation and the ability to save money, Plug Flow Tank (PFT) could still be a viable and effective solution to the problem, especially in a scenario where the inflow wastewater is relatively steady and any changes in the quality of the effluent cannot cause any problems. On the other hand, in cases where uniform and stable effluent quality is paramount and especially in situations where strict legislation is being enforced, the Membrane Bioreactor (MBR) is the solution that is evident. Its ability to produce consistent and high-quality effluents with a small variation is applicable in the plants with small discharge, significantly variable influent conditions, water recovery goals or limited space to upgrade.

The high consistency of the MBR shown in these results is based on a simplified model that assumes the membrane works perfectly, with no clogging or fouling. In real operation, membranes do foul and that can increase energy use and require more maintenance, and eventually can affect performance over time. These simulation results show the MBR's best possible stability. In an actual plant, achieving this level of reliability requires good fouling management, which adds to operational effort and cost.

Lastly, the PFT and MBR do not need the most advanced system as a solution. It is the selection of technology that serves the special needs in the project, site conditions, wastewater nature, and extent of change in the quality of effluent that is acceptable.

4. LIMITATIONS AND FUTURE SCOPE

This study provides a controlled comparative analysis using stochastic influent generation. And so a major limitations should be that the simulations were conducted under steady-state conditions and used a generalized ASM3 model. Real-world operational complexities such as dynamic diurnal flow patterns, transient shock loads, membrane fouling kinetics, and detailed energy consumption were not explicitly modeled. Future work should focus on dynamic simulation under time-variable influent profiles to assess system response to shock loads. Incorporating more advanced models that account for membrane fouling and a detailed life-cycle cost analysis would provide a more comprehensive comparison for engineering decision-making. Extending this framework to evaluate other advanced treatment configurations would also be valuable.

5. CONCLUSIONS

This study employed a stochastic simulation-based approach to compare the performance of a conventional Plug Flow Tank (PFT) and a Membrane Bioreactor (MBR) under realistic, variable influent conditions. The objective was to determine how each reactor configuration affects effluent quality stability by providing an evidence-based framework for system selection. The results demonstrate that both the PFT and MBR systems are capable of reaching similar maximum removal efficiencies for organic matter (COD, BOD) and solids (TSS). However, a key difference lies in their operational stability. The MBR produced results with a much narrower distribution and higher consistency for all performance metrics. In contrast, the PFT exhibited greater variability particularly in the removal of TSS. It occured due to its reliance on gravitational settling which is more susceptible to influent fluctuations and changes in sludge settleability. Though statistical tests showed no significant difference in the mean performance between the two systems, the substantially lower variance of the MBR indicates superior operational reliability. In summary, the choice between a PFT and an MBR is not merely about peak treatment ability. It is about selecting the system that best matches the project's specific requirements for reliability and its ability to handle variable influent conditions. The PFT remains a feasible and cost-effective solution for projects with relatively stable influent where intermittent effluent variations can be tolerated. Due to MBR's membrane filtration, it is the evidently more suitable option for facilities which requires consistent, high-quality effluent to meet strict discharge standards and handle highly variable loads.

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