Development and Performance Assessment of a Novel Integrated MSBR for Sustainable Domestic Wastewater Treatment

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Abstract—**This study presents a novel integrated modification of the Sequencing Batch Reactor (MSBR), combining the operational flexibility of conventional SBRs with the biomass retention and stability of a Moving Bed Biofilm Reactor (MBBR) through the incorporation of an upstream equalisation tank containing floating media and diffusers. The performance of the MSBR was evaluated against a conventional SBR and an MBBR under identical operating conditions. Over a 12-month monitoring period, influent and effluent samples were analysed for 25 physicochemical parameters representing organic load, nutrient dynamics, physical water quality, and mineral or trace element composition. Statistical analyses were conducted using IBM SPSS Statistics version 25. The MSBR consistently achieved the highest treatment performance. COD and BOD removal efficiencies reached 92.2% and 92.4%, compared with 88.5% and 88.7% in the MBBR and 82.6% and 82.9% in the SBR. Total nitrogen reduction was also higher in the MSBR (91.1%) than in the MBBR (79.9%) and SBR (85.7%), while total phosphorus removal reached 96%, outperforming both the MBBR (79.4%) and the SBR (89.5%). Sulfate removal remained moderate across all systems (MBBR 65.8%, MSBR 64.9%, SBR 57.1%). Although the SBR showed slightly higher oil and grease removal (83.4%), this marginal difference is outweighed by the MSBR's superior nutrient and organic matter removal. Seasonal and monthly analyses confirmed the operational robustness of the MSBR. Overall, the results demonstrate that the integrated MSBR is a reliable and superior alternative for sustainable domestic wastewater treatment.**

Index Terms—**Biofilm carriers, Moving bed biofilm reactor, Modification of the sequencing batch reactor, Pollutant removal efficiency, Sequencing batch reactor.**

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I. Introduction

A critical global environmental challenge is posed due to the rapid increase in population, urbanization, and industrial activities. Besides, one of the major sources of aquatic degradation that threatens human health and ecosystem integrity is due to the insufficiently treated domestic wastewater (Sam et al., 2021). For the sake of solving this huge issue, many biological treatment plants were built, among those, sequencing batch reactor (SBR) and moving bed biofilm reactor (MBBR) were the most common ones, because beside to their cost-effectiveness, they can efficiently reduce both organic matter and nutrients. Suspended biofilm carriers are the main component in the MBBR that leads to biomass retention enhancement, making the system resilient to the shock loads of organic and hydraulic stress (Sohail et al., 2020). The SBR is flexible when it comes to aeration control and reaction time due to the successive phases of filling (1 h), reaction (6 h), settling (1 h), and decanting (1 h) (Dey et al., 2024). Recently, SBR modification in its configuration has become the center of attention, primarily in the sequencing of the reaction with aeration patterns to improve nutrient removal (Khan et al., 2022).

In the present study, SBR is modified by integrating the robust biomass retention of MBBR with the operational flexibility of SBR. This SBR is modified modification of the SBR (MSBR) by incorporating an upstream equalization tank with the high-density polyethene (HDPE) carriers to enhance the stability and buffering with the addition of diffusers to provide the needed dissolved oxygen (DO) and keep the media floating at the same time as exhibited in Fig. 1, unlike the previous modifications, which were done in the same SBR basin, In terms of economic considerations, depending on Zhinda, (2025), the MBBR system represents the highest upfront cost among the three technologies. For instance, when treating 100 m^3 of wastewater, the packaged-unit cost of an SBR is roughly 60% of that of an MBBR, while the MSBR requires about 75% of the MBBR investment. A comparable

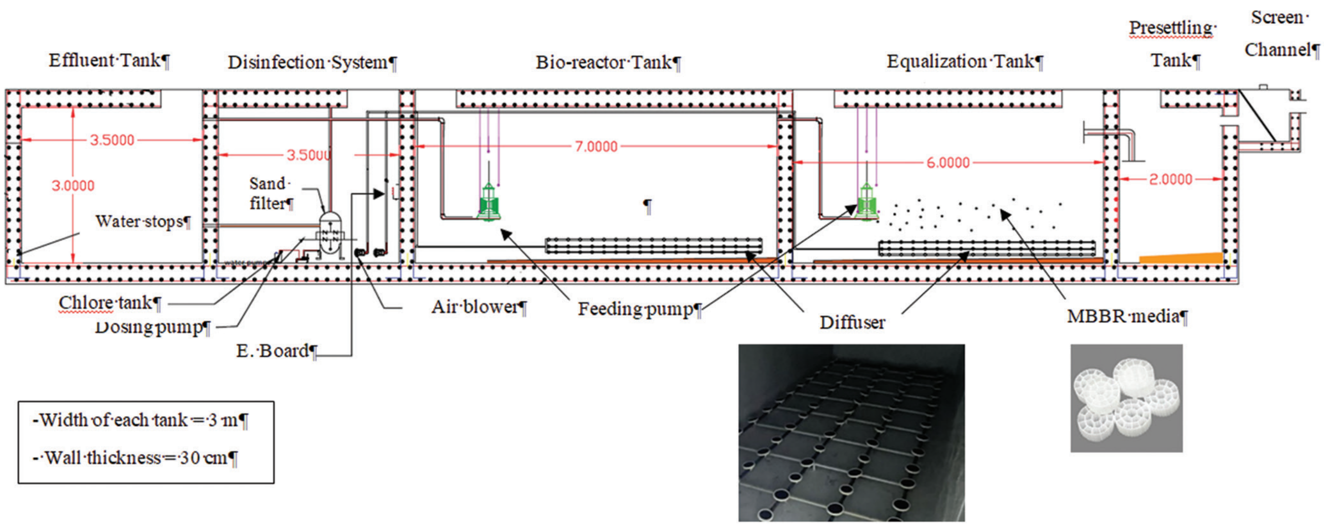

Fig. 1. Schematic of a modified sequencing batch reactor.

trend is observed in the cost of the electrical control boards: The SBR board costs approximately 60% of the MBBR equivalent, and the MSBR board is around 65%, positioning it close to the SBR and still notably more economical than the MBBR system. These differences highlight that the MSBR provides a more balanced cost profile while enhancing treatment performance. However, this novel design isn't just to propose a new configuration, but also to assess its performance compared to conventional SBR and MBBR based on effluent quality. Therefore, the objectives of this study are mainly to assess the performance of removing overall pollutants, including organic loads (chemical oxygen demand [COD], biochemical oxygen demand [BOD]), nutrients (total nitrogen [TN], NH_4^+–N, total phosphorus [TP]), and key physicochemical parameters, compared to the conventional SBR and MBBR systems during 12 months from July 2024 to June 2025. Then, determining the superiority of the novel MSBR regarding operational stability and overall pollutant reduction using different analyses of monthly and annual datasets. Finally, generating comparative evidence in selecting technology to guide decision-making in regulatory compliance and future planning of the infrastructure of the wastewater treatment. Therefore, by addressing these aims, this study fills the gap that exists in knowledge and also provides direct insight into the effectiveness of the proposed MSBR configuration, which offers theoretical and practical contributions to the design and operation of sustainable domestic wastewater treatment facilities.

II. Literature review

SBR is common in treating domestic wastewater due to its simplicity, efficiency, and cost-effectiveness (Daneshgar, et al., 2024). Therefore, recently, the system's configuration modification has been intensified in order to enhance the removal of nutrients, biomass stability, and energy performance improvement. For instance, Al-Rekabi, et al., (2021) reported that the conventional SBR has been developed into a sequencing batch biofilm reactor, in which biofilm-supporting media are introduced into the reactor basin. This configuration enables microorganisms to attach and grow on carrier surfaces, providing higher biomass retention compared to suspended-growth systems. The presence of fixed biofilms can improve nitrification efficiency, enhance organic matter degradation, and increase operational stability under fluctuating influent loads. However, because biofilm development occurs within the same tank used for fill-react-settle cycles, hydraulic buffering is limited, and the system may still be sensitive to sudden changes in influent quality or volume.

While Kassim et al. (2023) have integrated aerobic granular sludge (AGS) into the operations of the SBR system, in which the intermittent aeration was applied under an anaerobic-aerobic-anoxic regime within a 4-h SBR cycle to treat low-strength domestic wastewater. In this modification, further to promoting the development of dense, well-settling granules (a size of ~1.8 mm), the result nearly eliminated phosphorus, along with the removal of ~90% COD, and ~80% ammoniacal nitrogen.

In addition, Dey and his colleagues in 2024 investigated a constructed step-feed cycle configuration (SSBR) by comparing it to a conventional SBR under similar conditions. They reported that even with reduced aeration requirements that result in lower energy demand, SSBR still removed ammonium (NH_4^+-N) and TN significantly, while the effectiveness of phosphorus reduction was maintained. This research is published in Effluent Quality Improvement in Sequencing Batch Reactor-based Wastewater Treatment Processes Utilising Advanced Control Strategies (2024). Furthermore, influencing the dynamics of the microbial community to optimize the removal of nitrogen, the intermittent aeration was explored. For this to be done, Svierzoski et al. (2025) have examined continuous-flow AGS systems under varying aeration schedules, which ranged between three and 12 h/day. They found that the microbial groups were promoted, which leads to the enhancement of

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the settleability of the granule; thus, this regime has a very balanced outcome that could improve organic matter removal and denitrification, while the nitrification was sustained. Their result is compatible with the study of (Ha Quan and Gogina, 2019), in which the efficiency of the nitrogen removal reached ~80% by modifying the operational cycle by introducing the anoxic phase. However, Ha Quan and Gogina used biocarriers, such as BioChip 25 at 10–20% concentration as well, which promoted the overall removal by ~20%. Another modification includes introducing a static decanter and continual chamber filling to get the best oxygenation efficiency and save expenses. This SBR Grundfos technology, which is developed by (Sionkowski, et al., 2025), does not need the circulation of the sludge because of its unique design that allows the sedimentation to be stable under any fluctuations.

Recently, dynamic modeling as a tool has become vital alongside experimental work for the newly developed systems. Daneshgar, et al., (2024) have developed a model (dynamic compartmental model) for the stimulation of phosphorus removal in treating malt-waste effluent using SBR. This model helps understand the influence of the spatial compartments and different reaction phases on phosphorus removal dynamics throughout the operational cycle, which offers an important framework for process optimization. Besides, (Tehrani, Sayedbarzani and Irajpoor, 2025) have used an artificial intelligence to enhance operational efficiency. (Hameed, et al., 2025) developed a system to monitor crucial parameters online. The system was operating at hydraulic retention times (HRT) of 24 and 8 h to improve the efficiency. The result illustrates that the HRT of 8 h was more effective regarding the pollutant removal efficiency in the effluent. The same result was found by Carrasquero-Ferrer, Pino-Rodríguez and Díaz-Montiel, (2025), in which they designed a continuous-flow SBR, which is called the intermittent cycle extended aeration system and assessed its performance of nitrogen (which was ~67–90%) and carbon removal (~85%) using a model.

III. Materials and Methods

A. Experimental Setup

In this system, the equalization tank operates at 100 m^3/day with approximately a 20% media fill ratio, with the main bio-reactor basin. A 20% media fill ratio was chosen as it offers a practical balance between biofilm surface area and effective hydraulic mixing. Higher fractions risk circulation restrictions, while lower ones limit biomass support, making 20% a well-optimized and stable choice for this system, as stated by Makki and Hasan (2025). The carriers used are Kaldnes-type cylindrical HDPE media with a specific protected surface area of about 600 m^2/m^3 (Fig. 1), allowing effective biofilm attachment and stable microbial activity. DO in the equalization tank is maintained near 2–2.5 mg/L through fine-bubble EPDM diffusers (40 diffusers in each tank, each diffuser has a 10-inch diameter) (Fig. 1), supporting sustained aeration and uniform mixing. Here, the simplicity of cyclic operation is preserved as the bio-reactor basin is unchanged, while the floating media with the optimal amount of DO enhances the partial organic removal, and flow equalization before the influent enters the main bio-reactor basin. All that without a big increase in energy consumption as demonstrated by the measured daily energy use by Zhinda in 2025, which is a profound and active company in Erbil, Iraq: 121.7 kW/24 h for the SBR, 211.8 kW/24 h for the MBBR, and 187.7 kW/24 h for the MSBR. This shows that the MSBR delivers improved performance while still avoiding the high energy demand associated with the MBBR configuration.

During a 12-month monitoring period, three pilot-scale reactors (MBBR, SBR, and MSBR) that were constantly fed with domestic wastewater were run at the same time at a wastewater treatment facility in Erbil city, and the system was continuously monitored and controlled through a programmable logic controller to ensure operational consistency. All reactors were operated under the same hydraulic conditions (including an influent flow rate of approximately 100 m^3/day, a HRT of 24 h, a solids retention time (SRT) of 12–20 days), operating conditions (temperature, pH, and DO concentration as shown in Table I), and comparable aeration intensity for mixing. Composite influent and effluent samples were collected monthly, which is recommended by EPA (2013), as a reliable method for characterizing wastewater quality, since it integrates multiple subsamples collected across a defined interval into a single representative sample. All samples were analyzed on the same day of collection and were kept in sealed polyethylene bottles inside an insulated ice-cooled container during transport, ensuring that temperature-related chemical or microbial changes were minimized. This approach reduces the influence of temporal variability and ensures that measured pollutant concentrations more accurately reflect the average conditions of the wastewater stream over time. Then the samples were immediately preserved and analyzed within 24 h to minimize alteration of water quality characteristics.

B. Analytical Parameters

The assessment covered 25 indicators representative of organic loading, nutrient dynamics, physical conditions, and ionic composition. Specifically, COD and BOD were used to evaluate organic strength; sulfate, TP, TN, and ammonium-nitrogen (NH_4^+–N) represented nutrient status. Physical quality was tracked through turbidity, total suspended solids (TSS), total dissolved solids (TDS), electrical conductivity (EC), oil and grease, pH, DO, and temperature. Hardness and alkalinity were assessed through total, calcium, and magnesium hardness, as well as total alkalinity. In addition, concentrations of selected ions and trace elements (Cl^-, Al, Na^+, K^+, Si, Sn, and Fe) were determined.

C. Analytical Techniques

Multiple analytical instruments and reference protocols were employed:

TABLE I
Illustrates the Average of the Influent/Effluent of pH, Temperature, Dissolved Oxygen, Chloride, and Aluminum Concentrations for Each Season from July 2024 to June 2025

Systems	Pollutant monitored	Unit	Influent/ Effluent	Summer	Autumn	Winter	Spring
MBBR	pH	-	Influent	7.4	7.2	7.7	7.4
			Effluent	7.7	7.7	7.4	7.9
	Temperature	°C	Influent	32.3	26.2	15.1	21.7
			Effluent	30.8	24.4	15.7	22.1
	DO	mg/L	Influent	0.6	1.67	3.94	1.26
			Effluent	4.26	5.21	5.99	5.16
	Chloride		Influent	117.77	124.89	104.06	140.02
			Effluent	105.75	153.76	106.39	142.47
	Al		Influent	0.09	0.1	0.06	0.07
			Effluent	0.14	0.34	0.12	0.12
SBR	pH	-	Influent	7.3	7.7	8.5	7.5
			Effluent	7.4	7.4	7.7	7.4
	Temperature	°C	Influent	24.3	26.3	14.5	20.1
			Effluent	23.9	25.1	15.7	20.1
	DO	mg/L	Influent	3.49	3.79	3.56	5.47
			Effluent	5.75	3.38	6.67	7.4
	Chloride		Influent	177.97	116.98	115.74	81.71
			Effluent	122.23	72.42	125.06	76.97
	Al		Influent	0.87	1.37	1.91	1.29
			Effluent	1.47	1.97	2.12	2.43
MSBR	pH	-	Influent	7.2	7.2	7.6	7.7
			Effluent	7.1	7.5	7.3	7.6
	Temperature	°C	Influent	27	23.1	16.8	21
			Effluent	26	22.6	17	19.7
	DO	mg/L	Influent	1.66	2.44	2.92	4.26
			Effluent	5.74	5.28	7.5	6.88
	Chloride		Influent	224.87	185.16	236.7	185.13
			Effluent	155.98	128.89	129.2	133
	Al		Influent	0.6	1.01	2.17	1.32
			Effluent	1.2	1.57	2.33	1.57

MBBR: Moving bed biofilm reactor, SBR: Sequencing batch reactor, MSBR: Modification of the sequencing batch reactor, DO: Dissolved oxygen

- A Lianhua multiparameter analyzer (model LH-MUP230 V11S) was applied for COD, TN, NH_4^+–N, TP, and turbidity (Fig. 2).
- BOD was determined with a dedicated respirometric BOD analyzer (OxiTop® system).
- TSS were quantified by vacuum filtration following the methodology described by Estefan et al. (2013).
- pH, EC, TDS, and DO were measured with a multiparameter probe equipped with an in-built thermometer for Temperature.
- X-ray fluorescence spectroscopy was used for elemental analysis of Na^+, K^+, Si, Sn, Fe, and Al.
- Classical titration procedures were applied for chloride (Mohr method), hardness fractions, and alkalinity, again based on Estefan, et al. (2013).
- Oil and grease were extracted and quantified gravimetrically in line with EPA Method 1664A (USEPA, 1999).

D. Efficiency Calculation

The efficiency of pollutant removal for each system was calculated using the following equation:

Fig. 2. Lianhua multiparameter analyser (model LH-MUP230 V11S).

$$\text{Removal efficiency (\%)} = \frac{C_{\text{Influent}} - C_{\text{effluent}}}{C_{\text{Influent}}} \times 100$$

Where $C_{influent}$ and $C_{effluent}$ represent the concentrations before and after treatment, respectively.

E. Statistical Analysis

Statistical analyses were performed with IBM Statistical Package for the Social Sciences Statistics version 25. Data normality was tested using the Shapiro–Wilk method. Monthly influent-effluent differences were evaluated by paired *t*-tests for normally distributed data, or by Wilcoxon signed-rank tests otherwise. To compare overall reactor performance across parameters and sampling periods, one-way analysis of variance (ANOVA) (for normally distributed data) or Kruskal–Wallis tests (not for normally distributed data) were employed. Statistical significance was established at $p < 0.05$ (Duthie, 2024).

F. Operational Variables

In this study, aluminum and chloride concentrations alongside DO, pH, and temperature were monitored every month as shown in Table I. DO, pH, and temperature were excluded from statistical evaluation because they represent operational variables that are routinely regulated to maintain optimal biological treatment efficiency. These factors are known to directly influence microbial metabolism, enzymatic activity, and the overall stability of treatment processes. For DO, although influent values may occasionally appear higher, this is a natural consequence of biological activity in the reactors. As microorganisms break down organic matter, they actively consume oxygen for respiration. This biological demand can temporarily lower the DO in the effluent unless oxygen is continuously supplied through aeration diffusers. In periods of higher organic loading, oxygen depletion becomes more pronounced, reflecting normal biological utilization rather than measurement inconsistency.

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Similarly, chloride and aluminum were not considered in comparative statistical tests. In wastewater treatment operations, chloride is commonly introduced as a disinfectant (primarily in the form of chlorine) to suppress pathogenic organisms and limit the proliferation of undesirable microbes (Wang et al., 2025; Zhong et al., 2025). The concentration of chloride in the effluent is sometimes higher than that in the influent, because when hypochlorite is applied for microbial control, a portion of the chloride may remain in solution. Aluminum, on the other hand, is generally applied as aluminum sulfate (alum), serving as a coagulant to improve effluent clarity by promoting the removal of suspended solids, phosphorus, and colloidal matter (Sun, et al., 2024). Thus, variations in chloride and aluminum levels largely reflect intentional chemical dosing rather than inherent influent composition.

The controlled addition of these agents in the MBBR, SBR, and MSBR systems enhanced nutrient and solids removal while supporting stable microbial activity, aligning with standard operational practices in domestic wastewater treatment.

IV. Results and Discussion

A. Removal Efficiency across Systems

All three reactor configurations exhibited strong treatment performance, with substantial reductions in contaminant concentrations (Table II and Fig. 3). In line with earlier studies (Paul, et al., 2022; Murshid, et al., 2023; Ameen and Aziz, 2024). Each system achieved over 80% removal of organic pollutants. Among the tested designs, the MSBR consistently achieved the highest overall removal efficiencies for most measured parameters. The high phosphorus removal efficiency in the MSBR (□96%) is attributed to enhanced retention and metabolic activity of Polyphosphate-accumulating organisms within the biofilm, stabilized loading conditions achieved through upstream equalization, and longer effective SRT, which together provide more favorable conditions for biological phosphorus uptake than conventional SBR and MBBR systems (Terada, et al., 2006). Regarding TN removal in MSBR, it exhibited a high removal efficiency of approximately 91.05%, which can be attributed to the stable ammonium loading and reduced influent variability achieved through upstream equalization. By moderating organic and nitrogen fluctuations, the equalization tank enabled a more resilient nitrifying community to develop on the carrier media, sustaining robust ammonia-oxidizing and nitrite-oxidizing activity even under changing influent conditions. In addition, the biofilm-anchored biomass supports simultaneous nitrification-denitrification dynamics within micro-gradients, enhancing overall TN removal compared to suspended-growth SBR systems. Similar improvements in nitrogen removal associated with equalized influent and biofilm-supported nitrification have been demonstrated in comparable reactor configurations (Di Capua, et al., 2022). However, for certain inorganic indicators, particularly magnesium hardness (Mg^{2+}), potassium (K^+), and iron (Fe), the MBBR system demonstrated superior performance compared to both SBR and MSBR. This may be attributed to the strong sorption capacity of the biofilm matrix, where extracellular polymeric substances can bind and retain divalent ions, such as Mg^{2+} and Fe^{2+} (Li, et al., 2022). Moreover, the continuous-flow operation of the MBBR allows a longer and more stable interaction between ions and the biofilm, enhancing removal through both adsorption and biological uptake. For monovalent ions, such as K^+, selective uptake by the microbial community may also contribute to the observed reduction (Anggayasti, et al., 2023).

TABLE II
Illustrates the Systems' Efficiency in Removing the Organic, Nutrient, and Physicochemical Parameters from July 2024 to June 2025

Pollutant monitored	Unit	Removal efficiency (%)		
		MBBR	SBR	MSBR
Organic				
COD	mg/L	88.48	82.63	92.18
BOD		88.67	82.87	92.4
Nutrient				
SO_4^{-2}	mg/L	65.75	57.09	64.89
TP		79.37	89.53	96.00
TN		79.91	85.65	91.05
NH_4^+–N		89.42	94.95	94.04
Physical				
Turbidity	NTU	77.94	85.21	89.31
TSS	mg/L	83.01	86.38	91.28
TDS		22.94	8.25	37.1
EC	μS/cm	4.4	3.93	5.03
Oil and grease	mg/L	78.49	83.37	82.2
Hardness and alkalinity				
Total hardness	mg/L as $CaCO_3$	20.26	16.39	22.27
Ca^{2+} hardness		16.47	13.02	21.89
Mg^{2+} hardness		36.32	34.53	31.1
Total alkalinity		50.38	61.86	64.81
Ions and element concentration				
Na^+	mg/L	8.98	4.45	36.48
K^+		65.11	66.08	55.97
Si		0.93	4.4	5.26
Sn		51.9	92.18	94.43
Fe		81.58	63.04	60.11

MBBR: Moving bed biofilm reactor, SBR: Sequencing batch reactor, MSBR: Modification of the sequencing batch reactor, DO: Dissolved oxygen, COD: Chemical oxygen demand, BOD: Biochemical oxygen demand, TP: Total phosphorus, TN: Total nitrogen, TSS: Total suspended solids, TDS: Total dissolved solids, EC: Electrical conductivity

B. Statistical Comparison of Treatment Systems Effectiveness

Within-system

For each reactor type (MBBR, SBR, and MSBR), statistical testing confirmed significant improvements in water quality ($p < 0.05$). Normality was first assessed using the Shapiro–Wilk test, after which paired t-tests or Wilcoxon signed-rank tests were applied to all measured parameters across the 12-month monitoring period.

Between-systems

Annual mean comparisons revealed clear differences in system performance for most parameters. No significant differences ($p > 0.05$) were observed for sulfate (SO_4^{2-}), oil

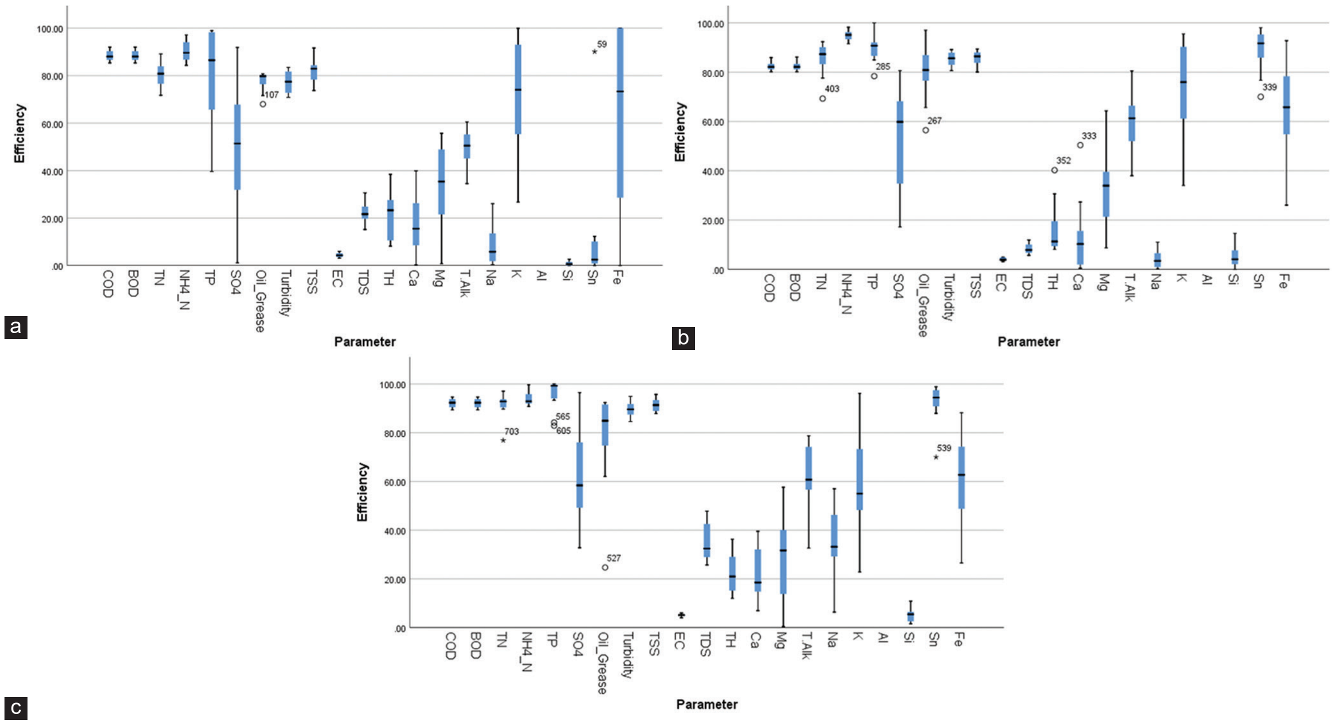

Fig. 3. Boxplot of the removal efficiency for each parameter by the systems from July 2024 to June 2025 (a) moving bed biofilm reactor, (b) sequencing batch reactor, and (c) modified sequencing batch reactor.

and grease, total hardness, calcium hardness, magnesium hardness, potassium (K^+), or iron (Fe) (Table III). Despite these exceptions, MSBR generally demonstrated higher overall removal efficiencies than both SBR and MBBR. The only consistent advantage of MBBR was its superior reduction of magnesium hardness, potassium, and iron, with respective mean values of 33.84, 72.04, and 21.00.

When treatment outcomes were compared on a monthly basis, no statistically significant variations were observed across systems ($p > 0.05$). This likely reflects variability in the reduction of specific pollutants by each system, which tended to balance out when parameters were considered collectively. Nevertheless, Kruskal–Wallis's rank analyses indicated that MSBR maintained the highest relative performance across nearly all months (Table IV).

The superior performance of MSBR may be attributed to its enhanced aeration control, optimized cycle sequencing, and improved biofilm dynamics, which collectively increase contact time and oxygen transfer, aligning with previous findings reported by Abu Hasan, Azahar, and Muhamad, (2025); Brotto, Kurt and Chandran, (2025); Liu, *et al*., (2025); and Wei, *et al*., (2024) Conversely, the capacity of MBBR to more effectively reduce Fe, Mg^{2+}, and K^+ suggests that its carrier biofilms may promote adsorption or precipitation processes particularly suited to these ions, supporting the observations of Sivalingam, et al., (2020). This highlights the need for further mechanistic studies into the role of biofilm-mediated pathways in metal removal. SBR, while showing lower nutrient removal efficiencies compared to MSBR, proved robust in oil and grease reduction. This is consistent with findings by Wang, et al. (2025) and Wichitsathian, et al. (2018), who highlighted the versatility of SBR in handling varying organic loads. The slightly lower oil and grease removal observed in the MSBR compared with the conventional SBR may be partly explained by the behavior of hydrophobic compounds in the equalization tank. Flow-equalization basins are known to act as pre-treatment units that buffer hydraulic and pollutant loads and can retain fats, oils and grease together with other floatable and settleable solids before downstream treatment. In our configuration, part of the oil and grease fraction may accumulate at the liquid surface or adhere to carrier and basin surfaces within the equalization tank, rather than being fully transferred to the main SBR basin for biodegradation or separation, which could slightly reduce the apparent removal efficiency measured across the MSBR train as a whole (Pintor, et al., 2016). Although the SBR removed oil and grease marginally more efficiently, the difference was small relative to other performance metrics.

Seasonal conditions influenced treatment behavior across all systems. During the warmer period of the year (late spring through early autumn), elevated temperatures stimulated microbial activity, leading to generally higher removal efficiencies for organic matter, nutrients, and slightly in oil and grease. Conversely, during the rainy and cooler months, the influent exhibited higher turbidity and TDS due to increased runoff and entrained particulates, as represented in Fig. 4.

A one-way ANOVA comparing overall removal efficiency among the three systems revealed a statistically significant difference ($F = 4.826$, $p = 0.008$), indicating that system type has a significant influence on treatment efficiency. However, the effect size was small (partial $\eta^2 = 0.013$), suggesting that

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TABLE III
Represents the Statistical Analysis using One-way ANOVA/Kruskal–Wallis Tests to Compare the Systems Depending on the Parameters

Pollutant monitored	Unit	Mean (or mean rank)			p-value (One-way ANOVA/ Kruskal–Wallis tests)	Post-Hoc (Tukey/ Games-Howell)
		MBBR	SBR	MSBR		
Organic						
COD	mg/L	88.435	82.4158	92.1417	0.000	<0.05
BOD		88.4492	82.4353	92.15	0.000	
Nutrient						
SO_4^{-2}	mg/L	49.94	51.7617	61.5417	0.394	>0.05
TP		13.5	17.04	24.96	0.024	<0.05
TN		9.83	17.58	28.08	0.000	
NH_4^+–N		90.1775	93.9683	94.9167	0.003	SBR and MSBR=0.766
Physical						
Turbidity	NTU	77.1858	85.3283	89.5125	0.000	<0.05
TSS	mg/L	81.7758	85.715	91.3225	0.000	
TDS		18.96	6.5	30.04	0.000	
EC	µS/cm	4.4433	4.0575	5.0792	0.007	SBR and MSBR=0.000
Oil and grease	mg/L	13.96	18.54	23.00	0.109	>0.05
Hardness and alkalinity						
Total hardness	mg/L as	13.67	19.25	22.58	0.111	
Ca^{2+} hardness	$CaCO_3$	17.295	12.8858	23.3742	0.196	
Mg^{2+} hardness		33.8417	31.8083	28.8533	0.758	
Total alkalinity		49.7358	59.1758	62.92	0.015	MBBR and MSBR=0.014
Ions and element concentration						
Na^+	mg/L	15.08	10.92	29.5	0.000	<0.05
K^+		72.0392	71.695	59.514	0.287	>0.05
Si		8.46	22.46	24.58	0.000	<0.05
Sn		7.25	22.08	26.17	0.000	
Fe		21.00	18.04	16.46	0.562	>0.05

MBBR: Moving bed biofilm reactor, SBR: Sequencing batch reactor, MSBR: Modification of the sequencing batch reactor, DO: Dissolved oxygen, COD: Chemical oxygen demand, BOD: Biochemical oxygen demand, TP: Total phosphorus, TN: Total nitrogen, TSS: Total suspended solids, TDS: Total dissolved solids, EC: Electrical conductivity, ANOVA: Analysis of variance

TABLE IV
Represents the Statistical Analysis using Kruskal–Wallis Tests to Compare the Systems' Monthly

Month	Mean rank			p-value (Kruskal–Wallis tests)
	MBBR	SBR	MSBR	
January	27.9	29.55	34.05	0.515
February	26.6	29.8	35.1	0.299
March	30.05	29.25	32.2	0.858
April	27.25	29.5	34.75	0.379
May	27.63	30.48	33.4	0.579
June	26.0	30.6	34.9	0.273
July	27.7	31.6	32.2	0.676
August	29.1	27.9	34.5	0.445
September	25.55	30.1	35.48	0.174
October	28.1	29.1	34.3	0.484
November	25.3	28.7	37.5	0.074
December	28.48	30.45	32.58	0.759

MBBR: Moving bed biofilm reactor, SBR: Sequencing batch reactor, MSBR: Modification of the sequencing batch reactor

TABLE V
One-way ANOVA Results Comparing Overall removal Efficiency among MBBR, SBR, and MSBR Systems across all the Parameters (When n=240 for Each System)

Tests of between-subjects effects (Dependent variable: Efficiency)					
Source	Type III sum of squares	Mean square	F	Significance	Partial Eta squared
System effect	11606.950[a]	5803.475	4.826	0.008	0.013

[a]R squared=0.013 (Adjusted R squared=0.011). MBBR: Moving bed biofilm reactor, SBR: Sequencing batch reactor, MSBR: Modification of the sequencing batch reactor, ANOVA: Analysis of variance

while MSBR outperforms MBBR and SBR, the magnitude of the difference is modest on a month-to-month operational scale, as shown in Table V. This confirms that although the systems behave similarly under short-term operational intervals, the MSBR configuration provides a meaningful advantage in sustained performance due to enhanced biofilm retention and oxygen transfer.

Overall, the comparison analysis emphasizes that treatment objectives and influent characteristics should guide system selection. SBR is suitable for influents with fluctuating organic loads, MBBR is beneficial for ion-rich wastewater, and MSBR is better suited for strict effluent regulations demanding maximum nutrient removal. This contextualized method maximizes system efficiency in accordance with local requirements, supporting sustainable wastewater management techniques.

C. Operational Challenges and System Response

Regarding carrier longevity, HDPE biofilm carriers typically have a service life of 10–20 years under normal operational conditions, as they are chemically resistant, mechanically stable, and not degraded by microbial activity (Zhinda, 2025). During real-time operation, occasional hydraulic surges caused a small amount of the floating media to drift toward the outlet zone, which required manual retrieval and, when necessary,

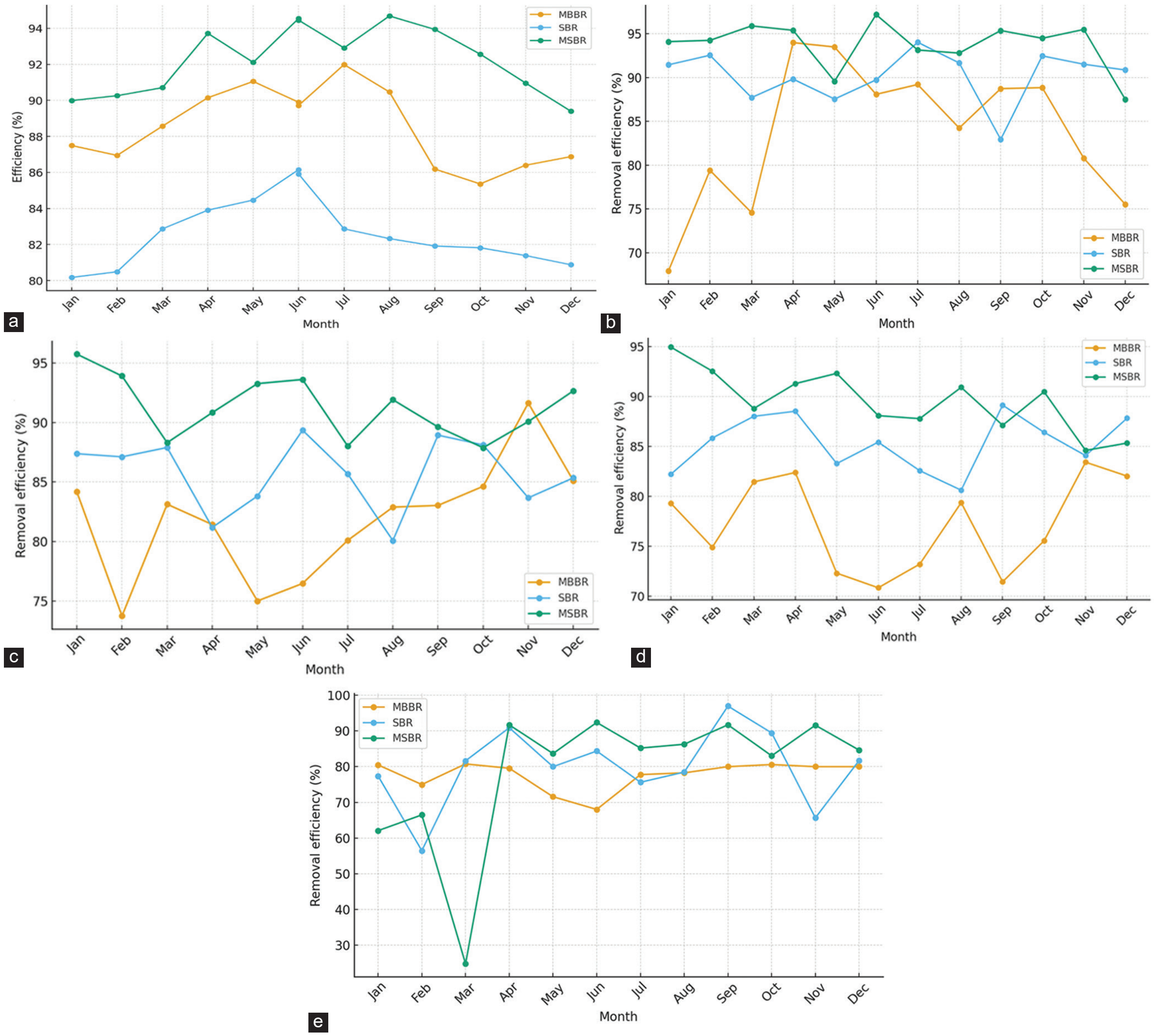

Fig. 4. Removal efficiency across three reactor systems (a) organic load (chemical oxygen demand and biochemical oxygen demand); (b) nutrient (total nitrogen, NH_3–N, total phosphorus); (c) total suspended solids; (d) turbidity; (e) oil and grease.

incremental replenishment. In the initial 2 days of startup, light foaming appeared on the reactor surface as the microbial community attached and matured on the media; this phase resolved on its own once stable biofilm growth was achieved. Over the entire study period, no clogging or aeration blockage was observed, indicating robust sludge handling and reliable hydraulic performance.

V. Conclusion

This study establishes the MSBR as a superior and innovative alternative to conventional SBR and MBBR systems for domestic wastewater treatment. The novelty of the design lies in relocating floating biofilm carriers and diffusers to the equalization tank rather than the SBR basin, creating a hybrid configuration that enhances buffering, biomass stability, and overall process efficiency. As a result, the MSBR achieved COD and BOD removals above 92%, TN removal exceeding 91%, and phosphorus elimination of 96%, consistently outperforming both the MBBR (COD/BOD ~88%, TN ~80%, P ~79%) and the SBR (COD/BOD ~83%, TN ~86%, P ~90%).

Although the SBR showed slightly higher oil and grease removal and the MBBR demonstrated strengths in ion and sulfate reduction, it is considered a minor operational compromise for the improved stability and nutrient removal performance of the MSBR. Therefore, the MSBR delivered the most balanced and robust treatment. These findings confirm its potential as a practical and sustainable solution, particularly for rapidly urbanizing regions, where stricter effluent standards and water scarcity demand more resilient wastewater technologies.

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