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Performance of an Integrated Sponge-MBBR and Membrane Bioreactor System for Poultry Slaughterhouse Wastewater Treatment

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ABSTRACT

In this study, the moving bed biofilm reactor (MBBR) combined with the membrane bioreactor (MBR) has been applied to treat poultry slaughter housing wastewater in Basrah city. The treatment unit consists of a poultry slaughter housing wastewater collection tank (250 L) and an MBBR tank with dimensions of L × W × H (60 × 30 × 50) cm. This tank contains a sponge carrier with a fill ratio of 40%, a mixer, a diffuser for aeration, and an open hole at a height of 10 cm for the discharge of treated water to the MBR. The membrane tank consists of a glass tank with dimensions L × W × H (50 × 30 × 60) cm containing a submerged, hollow ultrafiltration (UF) membrane unit. This study aimed to evaluate the efficiency of a sponge moving bed biofilm reactor (S-MBBR) system coupled with an MBR in treating wastewater from poultry slaughterhouses. At 6 h, the removal efficiencies for chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD), and total suspended solids (TSS) were approximately 84.52%, 87.64%, and 91.5%, respectively. As the time increased to 12 h, the removal efficiencies improved to 87.42% for COD, 89.60% for BOD, and 95.5% for TSS. The highest treatment efficiency was achieved at a hydraulic retention time (HRT) of 24 h, with COD, BOD, and TSS removal efficiencies of 98.16%, 95.64%, and 99.50%, respectively, yielding final effluent concentrations of 32.11 mg/L COD, 32.50 mg/L BOD, and 3.81 mg/L TSS. The results demonstrate that increasing the HRT significantly improves the removal of organic matter and suspended solids. Overall, the integrated S-MBBR-MBR system provided stable and efficient treatment of poultry slaughterhouse wastewater, with the best overall performance achieved at an HRT of 24 h. At HRTs of 6 and 12 h, the integrated S-MBBR–MBR system achieved COD removal efficiencies of 84.52% and 87.42%, respectively. Similarly, BOD removal improved from 84.52% and 86.72% in the MBBR to 87.64% and 89.60% in the integrated system. The most pronounced improvement was observed for TSS removal, which increased from 77.50% and 78.02% in the MBBR to 91.50% and 95.50% in the integrated system at HRTs of 6 and 12 h, respectively.

1. INTRODUCTION

The expanding human population and rising demand for poultry are driving the poultry industry's current rapid rise. Many of the waste products produced by poultry farms can also be utilized to produce biogas [1, 2]. Large amounts of wastewater produced during the killing, processing, and cleaning processes (20 L or more per bird) are a defining feature of slaughterhouses and meat processing facilities. This kind of water is regarded as one of the most contaminated wastewater types. Pet food and fertilizers are made from solid organic waste, but the liquid phase needs to be properly treated before being disposed of. High concentrations of microorganisms and organic loads derived from proteins, lipids, excrement, carcass residues, and blood are characteristics of poultry slaughterhouse wastewater (PSW) [3-6]. Membrane systems demand a significant amount of capital investment and annual maintenance, but they are very effective and stable with strong wastewater [7, 8]. A membrane bioreactor (MBR) is a cutting-edge technique that has shown better performance in generating bioenergy, removing pollutants, and having low fouling propensity. However, the biggest disadvantage of this technique is salt build-up. MBRs are capable of removing more than 80% of all organic carbon, PO_4^-, NH_4^+, and developing pollutants from wastewater [9-10]. A previous study evaluated the performance of an A/O moving bed biofilm reactor (MBBR) system in removing organic matter and nutrients from domestic wastewater at different gas-to-water ratios. A laboratory system operating with continuous upward flow was used, consisting of an anaerobic reactor followed by an aerobic reactor in equal volumetric ratios (50% each), with full internal nitrate recirculation and an 18 h hydraulic residence time. The results showed that the gas-to-water ratio had no significant effect on the removal efficiency of chemical oxygen demand (COD) and ammonium ions (NH_4^+-N), with removal rates exceeding 90% under various operating conditions. In contrast, the results showed that the removal of total nitrogen (TN) and total phosphorus (TP) was affected by changes in the gas-to-water ratio. A 7:1 ratio achieved the highest nutrient removal efficiencies while maintaining an operating environment suitable for nitrification and denitrification processes [11]. A previous study indicated that the hybrid moving bed membrane bioreactor (MBMBR), which combines MBBR and MBR technologies, achieved higher levels of pollutant removal efficiency compared to using each system separately. The removal efficiency in the MBMBR system was recorded at approximately 73.5%, compared to 62.5% for the MBR system and 50% for the MBBR system. This performance is attributed to the integration of moving-layer biological treatment processes with membrane separation, which contributed to improved wastewater treatment performance [12]. A previous study demonstrated that to benefit from the integration of different treatment technologies in industrial wastewater treatment, an integrated sequence of treatment units was adopted, including an MBBR, followed by an MBR, and then a direct-contact membrane distillation unit (DCMD). The MBBR stage was used as the initial biological treatment stage to reduce the pollutant load entering the MBR unit. The MBR system also served as a second biological treatment stage, in addition to its role as a pretreatment before the DCMD stage. The DCMD unit represented the final stage for producing high-quality water [13]. A previous study evaluated a hybrid system combining a moving bed biofilm reactor and a membrane bioreactor (MBBR-MBR) for treating wastewater from the textile industry. The results showed a removal efficiency of approximately 92% for COD and 95% for biological oxygen demand (BOD), in addition to complete removal of total suspended solids (TSS). These results indicate the hybrid system's ability to reduce pollutant concentrations and improve the quality of treated water under the studied operating conditions [14]. This study's objective is to develop a highly efficient and sustainable integrated treatment system for slaughterhouse wastewater (especially poultry slaughterhouses) with high organic loads and solids, achieving high removal efficiency and adhering to environmental standards while reducing space and operating costs.

2. MATERIALS AND METHODS

2.1 Description of the constructed unit

The major parts of the constructed unit are the feed tank, sponge moving bed biofilm reactor (S-MBBR), pumps, mixers, control panel, aeration systems, MBR (Hollow fiber MBR), and effluent collection tank. Figure 1 shows photos and a schematic diagram of the constructed unit. Table 1 shows design parameters. Table 2 shows membrane module information.

Table 1. Design parameter

Parameter	Value
Working Volume	80 L
Flow Rate	(13.3, 6.6, 3.3) L/h
Hydraulic Retention Time (HRT)	(6, 12, 24) h
Porosity	(90-95)%
Specific Surface Area	1200 m^2/m^3

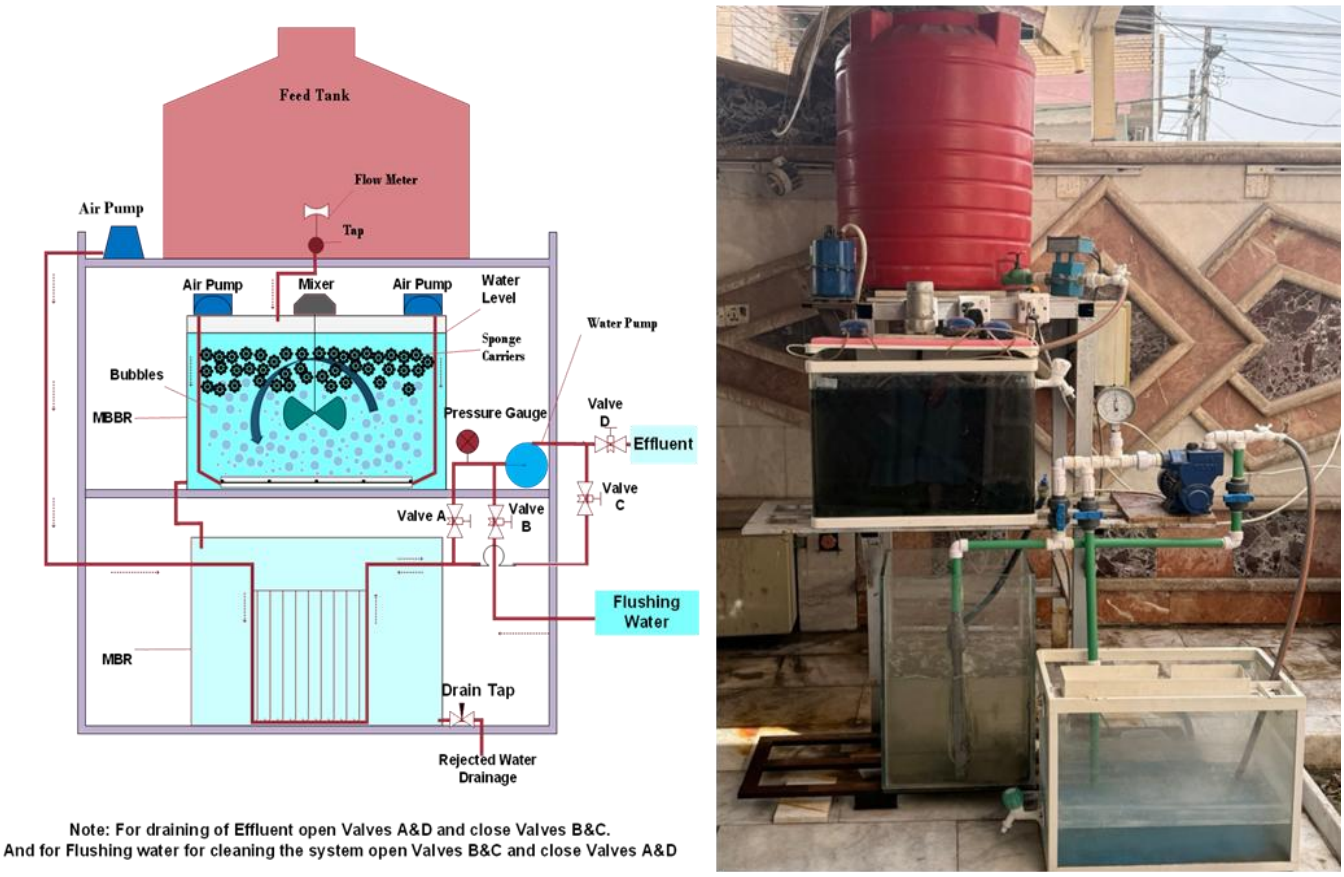


Figure 1. Schematic diagram and photo of the constructed unit

Table 2. Membrane-module information

Item Type	JF-SMBR-10	JF-SMBR-15	JF-SMBR-20
Membrane Area (m^2)	10	15	20
Membrane Filament Material		PVDF Hollow Fiber Filter Membrane	
Pore Size (um）		<0.1	
Filtration Type		Negative Pressure Suction	
Size H × W × T (mm)	1135 × 535 × 45	1680 × 535 × 45	2230 × 535 × 45
Backwash Pressure (MPa)		<0.05	
Suction Pressure (MPa)		-0.01 ～ -0.05	
Chemical Cleaning Agents		Hydrochloric Acid / Citric Acid / Oxalic Acid / Sodium Hypochlorite / Sodium Hydroxide	

2.2 Experimental processes and methods

Raw wastewater samples were drawn from different poultry slaughterhouses at Aljuniana, Aljazera, and Abu Alkaseeb in the city of Al Basrah. Samples were also collected from neighboring villages, places, and cities where many poultry slaughterhouses exist, following concerned districts' slaughtering restrictions and regulations. Daily quantities of raw wastewater from poultry slaughterhouses were collected in clean plastic drums and regularly transported to the experimental system site. Before being fed into the collection tank, the raw water underwent a simple physical pretreatment process. A mesh screen with a pore size of 5 mm was installed for preliminary screening. This involved filtering out large solids such as bones and feathers, as well as manually skimming the surface fat layer after a short period of standing time to allow the fat to float. This process aimed to reduce the organic and fat load entering the system and ensure the stable operation of the experimental system. The pretreated water was then collected in the collection tank and used to feed the treatment unit for experiments conducted under the specified operating conditions. After the treatment process was completed, the samples were collected from the system and transported to the laboratory of the College of Engineering at the University of Basrah. There, the necessary physical and chemical tests were performed to evaluate the efficiency of the system used for treating poultry slaughterhouse wastewater. The reactor was operated continuously under successive hydraulic retention time (HRT) cycles, with each HRT cycle maintained for a total of Each HRT condition was maintained until steady-state conditions were achieved.

Steady-state conditions were achieved by the end of the eighth week of the start-up period, as evidenced by the stability of COD removal efficiency at 76.54% with minimal fluctuations, confirming the stable performance of the reactor and the stable microbial activity. Before data collection at each HRT cycle, the system was allowed to undergo an acclimation and stabilization phase to ensure biological adaptation to the operating conditions. No physical cleaning of the sponge holders or sludge removal was performed between HRT cycles; only the inlet water flow rate was adjusted to achieve the desired HRT cycle, allowing the system to transition gradually. Steady-state conditions were defined based on the stability of key performance indicators, including stable COD concentrations and removal efficiency in the effluent water, as well as stable pH and dissolved oxygen (DO) values. A clear operational Table 3 describes the start-up and steady-state.

Wastewater samples were collected over a three-month period, from July 1st to September 30th, representing the actual operating conditions of Basra slaughterhouse wastewater. Tests were conducted under different HRT conditions: 6, 12, and 24 h. For each HRT value, 13 tests and analyses were performed during the study period to accurately represent the temporal variations in wastewater characteristics.

Table 3. The start-up period and steady-state stage

State	Duration	HRT (h)
Start Up	2 months	24 h
Steady State	3 months	6, 12, 24 h

Note: HRT: hydraulic retention time.

2.3 The methodology of the experimental work

A 90-liter Moving Bed reactor was operated. It was inoculated with activated sludge from the Al-Thaghar wastewater treatment plant. Samples were taken from the reactor inlet and outlet, and then from the membrane tank outlet once every seven days. With the exception of pH, DO, and temperature, which were tested daily, pH, temperature, total dissolved solids, and DO values were recorded immediately after sampling. Samples used to measure the remaining parameters were kept at 4 ℃ before being transported to the laboratory. The seeds are added to the MBBR reactor, followed by the addition of sponge carriers to the reactor at a 40% filling rate. Then, wastewater from the chicken slaughterhouses is added. Aeration and mixing processes begin sequentially. The water exiting the moving bed is then transferred to the membrane basin (90 L) via pipes by gravity, passing through the immersed hollow membrane with a pore size < 0.1 μm. Air is then pumped into the membrane through the aeration port by an air pump. Aeration helps clean the membrane filament surface during membrane unit operation. The typical aeration rate for a membrane unit (membrane cross-sectional area projected per membrane unit) is 120 to 180 standard cubic meters per ($m^2 \cdot h$), or 3.6 to 5.4 m^3/h per membrane unit [15]. For water removal, a suction pump with a pressure not exceeding 0.5 bar is used to extract the treated water from the membrane unit. To ensure quantitative performance, a flow control valve is installed on the suction pump discharge side, along with a pressure gauge. The flow is electronically controlled, and a backwash control valve is also used, as shown in Figure 1. To drain the treated water, valves A and D are opened, and valves B and C are closed; for backwashing, the system opens valves B&C and close valves A&D. The remaining water in the membrane tank is drained through a dedicated opening located at the tank's edge. It's worth noting that the presence of sponge carriers in the moving bed reactor tank has eliminated the need for chemical flushing. These carriers have effectively contributed to the biological treatment of organic matter in slaughterhouse wastewater, enhancing system efficiency and reducing operational requirements. Analysis of transmembrane pressure (TMP) trends over time showed a gradual increase in the early operating phase, followed by a period of relative stability. The initial rise is primarily attributed to pore blocking, while the subsequent increase indicates the formation of a layer of sludge on the membrane surface. When using a sponge carrier, a clear slowdown in the rise of TMP was observed, indicating the carrier's ability to improve flow distribution and reduce near-surface particle deposition. These results are consistent with theoretical inputs linking improved sludge distribution to reduced layering in membrane systems.

2.4 Analytical methods

The entire test was typically conducted using a spectrometer Dr5000 in the sanitary laboratory of the University of Basrah's Department of Civil Engineering. Additionally, ovens, digital equipment, sensitive scales, and BOD devices were employed in some of the testing. BOD was evaluated using the Oxidirect instrument handbook (BOD, V2.3) [APHA] [16]. COD (standard procedures for water and wastewater) [17]. As mentioned before, the considered parameters were DO, pH, Temperature, Electrical Conductivity, and Total Dissolved Solids (HACH-HQ30d). Mixed Liquor Suspended Solids and TSS (Drying oven and analytical balance).

The removal efficiency (R) of any parameter was calculated as:

$$R\% = \frac{[\text{Influent} - \text{effluent}]}{\text{Influent concentration}} \quad (1)$$

3. RESULTS AND DISCUSSION

As shown in Figure 2, the experimental period for different operating stage modes continued in both the hollow MBR and the MBBR.

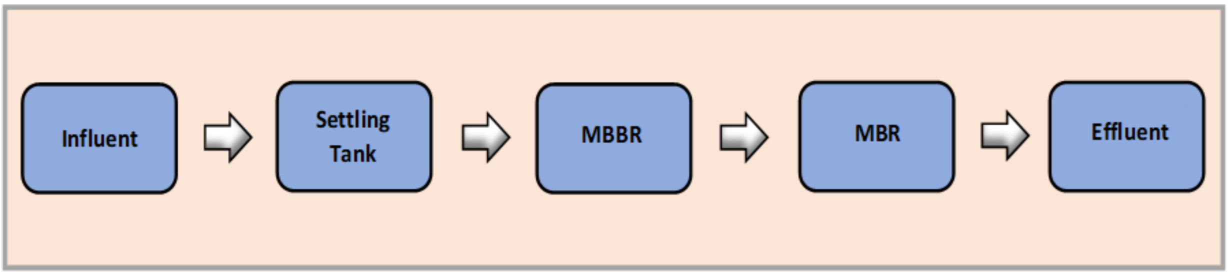


Figure 2. Process of experimentation

To find the reactor stage that yields the greatest results, operational optimization is utilized. This procedure was completed in three stages with different HRT; each treatment has its own set of parameters. Table 4 shows raw wastewater.

Table 4. Raw wastewater

Parameter	Range
COD (mg/L)	1289-1982.5
BOD (mg/L)	432.8-923.4
TSS (mg/L)	627-813
pH	5-8.9

Note: COD = chemical oxygen demand; BOD = biological oxygen demand; TSS = total suspended solids.

3.1 Results for steady state

3.1.1 Removal of chemical oxygen demand and biological oxygen demand

The concentrations of influent COD and BOD in the MBBR reactor based on sponge carrier with a filling ratio of 40%. The values of the concentrations in the reactor and the removal efficiency for both parameters at different hydraulic retention times (6 h, 12 h, and 24 h) and during the aeration cycles (3 on/3 off). Weekly periodic monitoring was performed for thirteen weeks of each HRT cycle. This monitoring included specific measurements of COD and BOD. At the beginning of the 6 h HRT cycle, the initial reading for the first week recorded a COD value of the influent (1872 mg/L), the effluent value of MBBR (441.4 mg/L), and the effluent value from combined MBBR and MBR (405.1 mg/L), with removal efficiency (78.36%). BOD influent value of 923.4 mg/L and the effluent of MBBR (245.53 mg/L), the effluent from MBBR and MBR (228.9 mg/L) with removal efficiency (75.21%). At the end of the study period in the thirteenth week, the final influent value of COD was 1582.6 mg/L and effluent value of MBBR was 265.08 mg/L, the effluent from MBBR and MBR (244.98 mg/L) with removal efficiency of 84.52%. BOD values for that cycle were recorded as 654.3 mg/L, 101.28 mg/L, 80.87 mg/L, and 87.64%, respectively. Similarly, the same methodology was applied to cycle 12 hrt. The influent, effluent from MBBR, effluent from MBBR with MBR, and removal efficiency readings for the first week showed COD were 1809.9 mg/L, 388.04 mg/L, 375.73 mg/L, and 79.24%. BOD values were 915.20 mg/L, 222.21 mg/L, 196.4 mg/L, and 78.54%, respectively. By the thirteenth week of this cycle, the final COD were 1730.4 mg/L, 244.5 mg/L, 217.68 mg/L, and 87.42%. BOD values were 713.63 mg/L, 94.77 mg/L, 74.21 mg/L, and 89.6%, respectively. For cycle twenty-four, the tests were conducted in the same manner. The initial reading for the first week recorded COD were 1668.39 mg/L, 264.25 mg/L, 249.74 mg/L, and 85.03%. BOD values were 763.2 mg/L, 173.7 mg/L, 157.6 mg/L, and 79.33%, respectively. By the end of the thirteenth week of cycle twenty-four, the final COD values were 1745.3 mg/L, 64.4 mg/L, 32.11 mg/L, and 98.16%. BOD values were 745.5 mg/L, 78.13 mg/L, 32.5 mg/L, and 95.64%, respectively. Tables 5-7 and Figures 3-8 show COD results. Tables 8-10 and Figures 9-14 show BOD results.

The sponge carriers in the MBBR system with membrane technology provide an integrated solution for slaughterhouse wastewater; the sponges provide an ideal environment for high-density bacterial growth to break down biodegradable and non-biodegradable organic bonds easily, while the membrane ensures the retention of all suspended organic particles and biomass, which explains the remarkable increase in COD and BOD removal efficiency in the final stage. The removal rate depends directly on the HRT. Sponge carriers act as a supportive medium for biofilm growth within the reactor.

Their three-dimensional porous structure provides a relatively large surface area, allowing for a greater number of sites available for microbial adhesion. This leads to the development of a stable biofilm compared to simply suspending biomass. Within the sponge's pores, a relatively protected environment exists, characterized by reduced hydraulic shear forces. This allows for the gradual growth of aerobic and anaerobic micro-zones within the same carrier. This variety of micro-conditions enhances the efficiency of organic pollutant and nitrogenous material removal. Furthermore, the sponge acts as a biomass reservoir, reducing the risk of bacteria being washed out of the system during changes in hydraulic or organic load. This increases performance stability and enhances shock load resistance. In addition, the presence of biomass fixed to the sponge contributes to reducing free suspended solids, which may indirectly improve the performance of the membrane unit and reduce the fouling tendency, although this effect depends on operating conditions and cannot be confirmed without direct measurements.

Increasing the time from 6 to 24 h provides the system with the following advantages:

1. Enhanced microbial contact: The 24 h period allows for greater interaction between microorganisms and contaminants, increasing adsorption and metabolism efficiency [18].
2. Decomposition of complex compounds: Some complex organic compounds require longer incubation periods to break their chemical bonds, which is not achieved in short periods such as 6 h [19].
3. Hydraulic stability: The longer time reduces the impact of hydraulic disturbances, helping to improve the quality of the discharged water and reduce suspended solids that contribute to the COD value [20].

These results are consistent with the findings of many researchers in this field. For example, the study [21] indicated that extending the hydraulic residence time necessarily improves the efficiency of COD and nutrient removal in bioreactors. Similarly, Chakawa et al. [5] confirmed that achieving removal efficiencies exceeding 90% often requires residence times of around 24 h in advanced oxidation systems.

3.1.2 Removal of total suspended solids

TSS refers to undissolved particles present in wastewater, such as organic matter residues, sludge, feathers, and dirt. They are among the most important indicators of poultry slaughterhouse wastewater quality. TSS are among the most important indicators of wastewater quality in poultry slaughterhouses, given their direct impact on water quality and the efficiency of subsequent treatment processes, as well as their role in increasing the likelihood of membrane blockage in membrane systems. Therefore, primary treatment processes focus on reducing TSS concentration through physical processes such as screening, sedimentation, and deglazing, resulting in the removal of a significant proportion of coarse and suspended solids.

Table 5. COD result at HRT 6 h

HRT (h)	Influent	EFF (MBBR)	R% (MBBR)	EFF (MBBR + MBR)	R% (MBBR + MBR)
6	1872	441.41	76.42	405.1	78.36
	1820.6	422.02	76.82	372.86	79.52
	1835.1	410.69	77.62	364.82	80.12
	1782.7	383.64	78.48	340.32	80.91
	1761.22	370.74	78.95	330.23	81.25
	1642.9	321.68	80.42	299.67	81.76
	1840.2	351.11	80.92	327.92	82.18
	1834.5	374.97	79.56	355.15	80.64
	1722.6	322.81	81.26	303.69	82.37
	1730.9	316.06	81.74	295.46	82.93
	1672.7	297.24	82.23	284.19	83.01
	1652.8	286.43	82.67	266.76	83.86
	1582.6	265.08	83.25	244.98	84.52
Mean ± SD	1790.20 ± 71.81	377.67 ± 41.92	78.94 ± 1.76	344.42 ± 33.86	80.79 ± 1.30

Note: COD = chemical oxygen demand; HRT = hydraulic retention time; EFF = effluent; MBBR = moving bed biofilm reactor; MBR = membrane bioreactor; SD = standard deviation.

Table 6. COD result at HRT 12 h

HRT (h)	Influent	EFF (MBBR)	R% (MBBR)	EFF (MBBR + MBR)	R% (MBBR + MBR)
12	1809.9	388.04	78.56	375.73	79.24
	1556.4	324.97	79.12	306.29	80.32
	1762.1	348.54	80.22	316.83	82.02
	1711.4	318.83	81.37	298.47	82.56
	1420.8	256.31	81.96	241.25	83.02
	1672.2	293.97	82.42	272.23	83.72
	1642.3	281.49	82.86	260.79	84.12
	1492.5	251.78	83.13	255.52	84.89
	1722.6	279.92	83.75	254.25	85.24
	1815.3	290.81	83.98	257.04	85.84
	1643.1	255.38	84.46	299.04	86.06
	1582.2	235.59	85.11	207.74	86.87
	1730.4	244.5	85.87	217.68	87.42
Mean ± SD	1658.55 ± 119.48	290.01 ± 44.82	82.52 ± 2.24	274.07 ± 44.98	83.95 ± 2.47

Note: COD = chemical oxygen demand; HRT = hydraulic retention time; EFF = effluent; MBBR = moving bed biofilm reactor; MBR = membrane bioreactor; SD = standard deviation.

Table 7. COD result at HRT 24 h

HRT (h)	Influent	EFF (MBBR)	R% (MBBR)	EFF (MBBR + MBR)	R% (MBBR + MBR)
	1668.39	264.25	84.16	249.74	85.03
	1458.6	217.26	85.14	196.26	86.58
	1378.4	190.28	86.22	163.56	88.16
	1982.5	259.11	86.93	216.09	89.1
	1624	194.07	88.05	153.95	90.52
	1862	202.21	89.14	147.09	92.1
24	1787	176.56	90.12	117.58	93.42
	1873.3	169.9	90.93	102.28	94.54
	1392.5	107.08	92.31	66	95.26
	1525.2	96.54	93.67	58.26	96.18
	1685.6	93.04	94.48	52.75	96.87
	1906.8	91.91	95.22	47.69	97.54
	1745.3	64.4	96.31	32.11	98.16
Mean ± SD	1693.81 ± 175.60	161.51 ± 53.84	89.88 ± 3.90	126.11 ± 67.83	91.21 ± 4.05

Note: COD = chemical oxygen demand; HRT = hydraulic retention time; EFF = effluent; MBBR = moving bed biofilm reactor; MBR = membrane bioreactor; SD = standard deviation.

Table 8. BOD result at HRT 6 h

HRT (h)	Influent	EFF (MBBR)	R% (MBBR)	EFF (MBBR + MBR)	R% (MBBR + MBR)
	923.4	245.53	73.41	228.9	75.21
	832.3	206.32	75.21	186.1	77.64
	872.41	222.46	74.5	204.66	76.54
	789.62	173.95	77.97	164.63	79.15
	784.21	158.01	79.85	145.7	81.42
	724.73	134.36	81.46	121.1	83.29
6	916.31	165.3	81.96	134.14	85.36
	892.92	149.56	83.25	123.75	86.14
	785.17	158.21	79.85	136.93	82.56
	764.3	120.53	84.23	100.42	86.86
	722.63	110.63	84.69	87.07	87.95
	742.52	119.76	83.87	104.99	85.86
	654.3	101.28	84.52	80.87	87.64
Mean ± SD	800.52 ± 88.74	158.92 ± 46.44	80.37 ± 4.08	139.17 ± 45.62	82.74 ± 4.43

Note: BOD = biological oxygen demand; HRT = hydraulic retention time; EFF = effluent; MBBR = moving bed biofilm reactor; MBR = membrane bioreactor; SD = standard deviation.

Table 9. BOD result at HRT 12 h

HRT (h)	Influent	EFF (MBBR)	R% (MBBR)	EFF (MBBR + MBR)	R% (MBBR + MBR)
	915.2	222.21	75.7	196.4	78.54
	625.32	128.19	79.5	112.49	82.01
	743.12	157.54	78.8	129.74	82.54
	752.31	145.94	80.6	118.41	84.26
	520.81	93.74	82	79.94	84.65
	672.62	119.26	82.4	85.17	87.43
12	630.54	116.01	81.6	103.91	83.52
	534.67	88.74	83.4	76.82	85.63
	783.24	115.91	85.2	96.46	87.68
	794.22	130.25	83.6	113.09	85.76
	712.62	108.31	84.8	90.85	87.25
	612.42	83.28	86.4	69.01	88.73
	713.63	94.77	86.72	74.21	89.6
Mean ± SD	692.71 ± 110.61	130.79 ± 40.45	82.10 ± 3.65	101.58 ± 34.78	85.36 ± 3.48

Note: BOD = biological oxygen demand; HRT = hydraulic retention time; EFF = effluent; MBBR = moving bed biofilm reactor; MBR = membrane bioreactor; SD = standard deviation.

Table 10. BOD result at HRT 24 h

HRT (h)	Influent	EFF (MBBR)	R% (MBBR)	EFF (MBBR + MBR)	R% (MBBR + MBR)
	763.2	173.7	77.24	157.6	79.35
	573.4	127.12	77.83	113.76	80.16
	432.8	104.69	75.81	93.26	78.45
24	854.7	176.92	79.3	157.52	81.57
	742.6	143.91	80.62	128.24	82.73
	753.9	132.3	82.45	115.72	84.65
	682.7	108.54	84.1	93.93	86.24

	772.6	123.73	85.82	107.3	87.68
	579.7	75.88	86.91	66.89	88.46
	640.2	74.9	88.3	66.96	89.54
	722.5	96.23	86.74	64.76	91.1
	820.8	92.99	88.67	51.3	93.75
	745.5	78.13	89.52	32.5	95.64
Mean ± SD	680.58 ± 111.78	117.18 ± 35.32	82.44 ± 5.35	93.55 ± 38.55	86.56 ± 5.82

Note: BOD = biological oxygen demand; HRT = hydraulic retention time; EFF = effluent; MBBR = moving bed biofilm reactor; MBR = membrane bioreactor; SD = standard deviation.

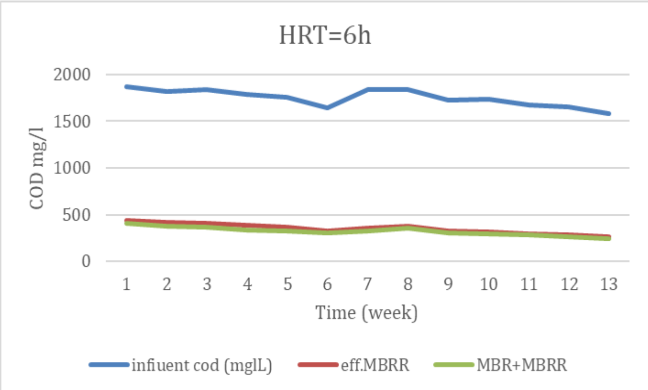


Figure 3. Profile of chemical oxygen demand (COD) concentration in hydraulic retention time (HRT) = 6 h

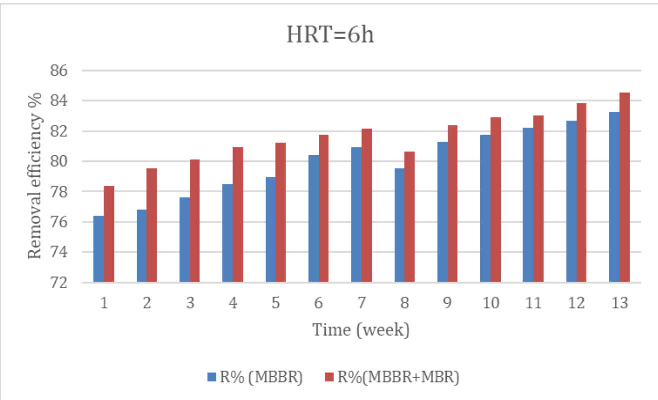


Figure 4. Profile of chemical oxygen demand (COD) removal rate in hydraulic retention time (HRT) = 6 h

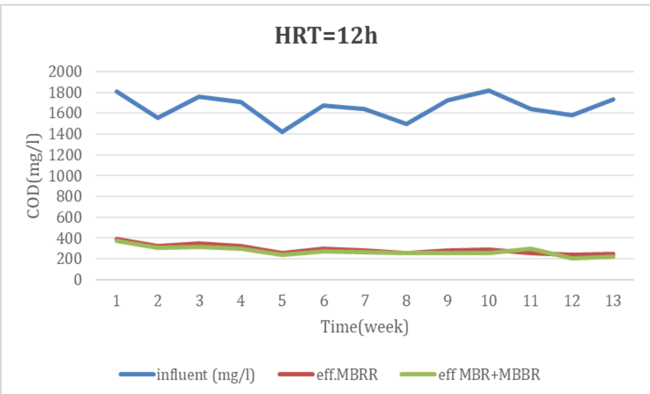


Figure 5. Profile of chemical oxygen demand (COD) concentration in hydraulic retention time (HRT) = 12 h

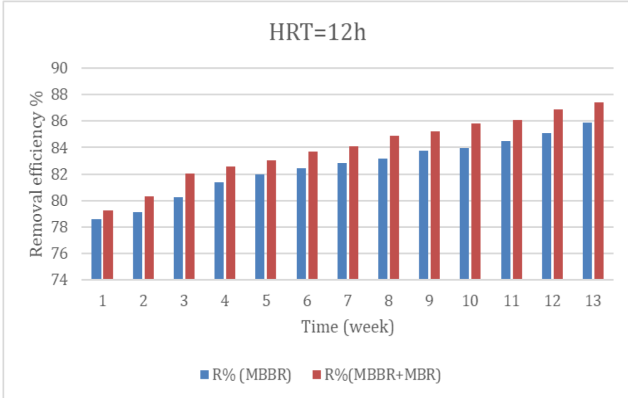


Figure 6. Profile of chemical oxygen demand (COD) removal rate in hydraulic retention time (HRT) = 12 h

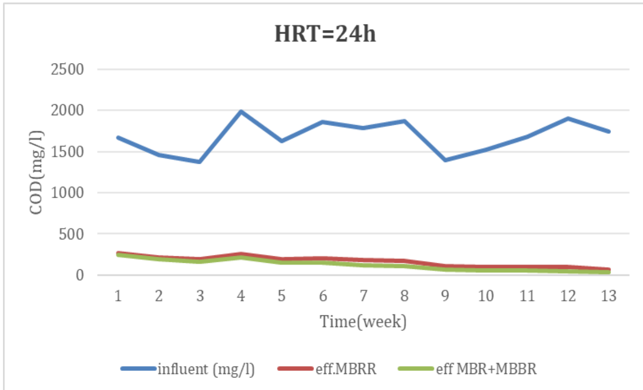


Figure 7. Profile of chemical oxygen demand (COD) concentration in hydraulic retention time (HRT) = 24 h

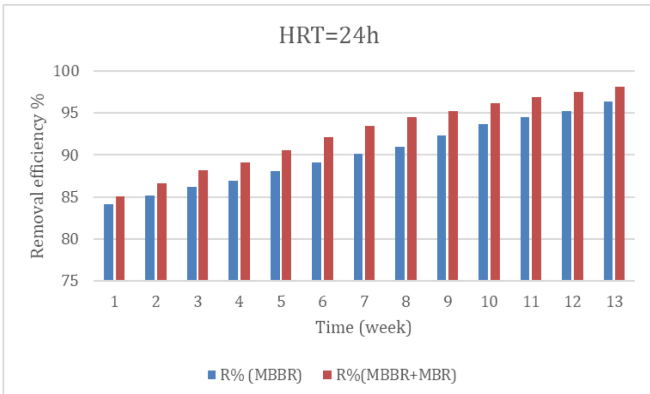


Figure 8. Profile of chemical oxygen demand (COD) removal rate in hydraulic retention time (HRT) = 24 h

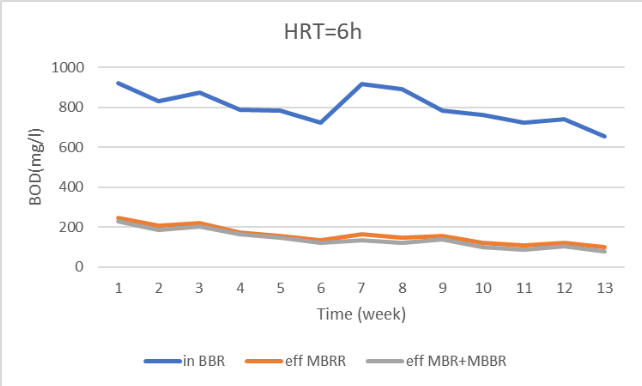


Figure 9. Profile of biological oxygen demand (BOD) concentration in hydraulic retention time (HRT) = 6 h

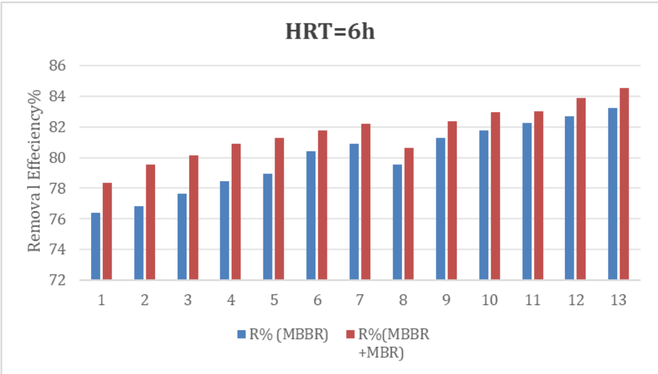


Figure 10. Profile of biological oxygen demand (BOD) removal rate in hydraulic retention time (HRT) = 6 h

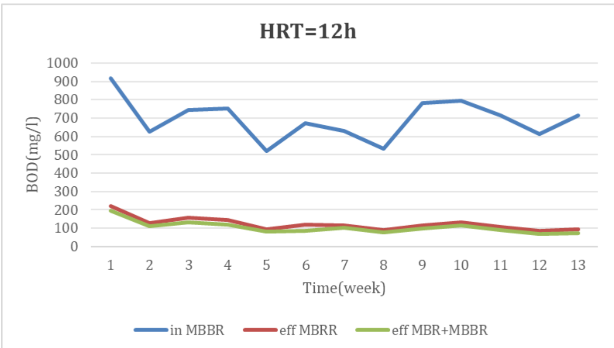


Figure 11. Profile of biological oxygen demand (BOD) concentration in hydraulic retention time (HRT) = 12 h

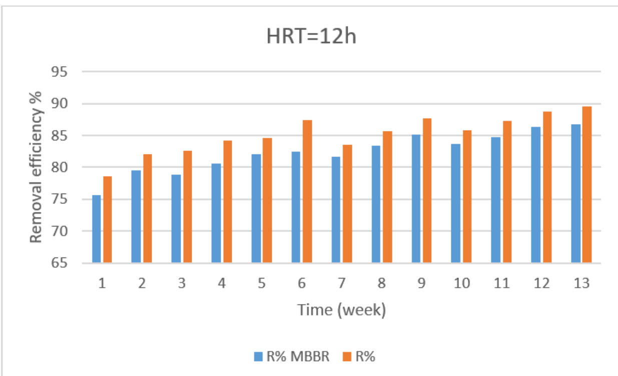


Figure 12. Profile of biological oxygen demand (BOD) removal rate in hydraulic retention time (HRT) = 12 h

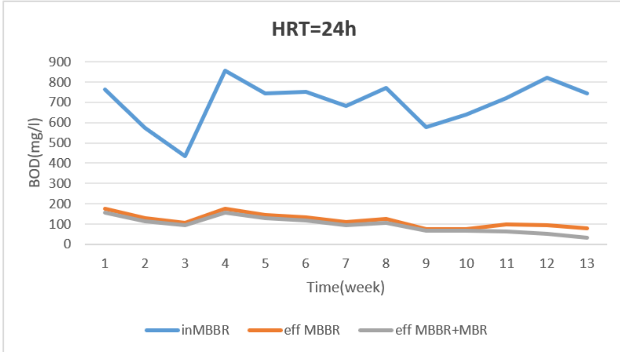


Figure 13. Profile of biological oxygen demand (BOD) concentration in hydraulic retention time (HRT) = 24 h

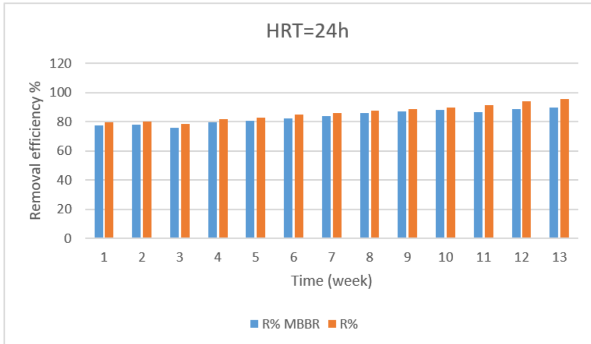


Figure 14. Profile of biological oxygen demand (BOD) Removal Rate in hydraulic retention time (HRT) = 24 h

In a bioremediation system using a Moving Sponge Bioreactor, the sponge carriers contribute to improved TSS removal by providing a large surface area for biofilm growth and stabilization, in addition to trapping suspended particles within the sponge's three-dimensional pores. This allows for increased contact time between pollutants and the biomass, which enhances the decomposition of suspended organic matter and reduces its concentration in the effluent. Furthermore, the continuous movement of the carriers within the reactor improves water mixing and prevents sludge buildup, thus maintaining the efficiency of the bioremediation process.

As the HRT increased from 6 to 12 and then to 24 h, the efficiency of suspended solids removal improved. This was due to the longer time allowed for particle retention within the sponge carriers and their biodegradation, as well as improved biofilm stability and increased microbial activity. This resulted in a gradual decrease in the concentration of suspended solids in the treated water and higher removal rates with increasing treatment time.

When the S-MBBR system was combined with an MBR, the efficiency of suspended solids removal increased even further. The submerged membranes acted as a physical barrier, preventing the passage of fine particles and remaining suspended solids. This resulted in the production of water with very low turbidity and extremely low suspended solids concentration, making it suitable for reuse or discharge according to environmental standards.

In general, the combined S-MBBR / MBR system is a highly efficient technology for removing total suspended solids from poultry slaughterhouse wastewater. This efficiency is attributed to the integration of retention and biodegradation within sponge carriers and membrane microfiltration, particularly when the system is operated under optimal DO and HRT conditions.

Tables 11, 12, and 13 show the total suspended solids concentrations and their removal rates at different HRT times (6, 12, and 24 h); Figures 15–17 show the total suspended solids removal rates.

3.1.3 pH

One of the most crucial factors that needs to be regularly monitored is pH. The outcomes were satisfactory and neither exceeded nor fell short of the limits necessary to finish the biological treatment process in the MBR and MBBR reactors. Samples were collected daily for measurement during the whole experiment, as shown in Figure 18, which displays the pH values through cycle modes. Regarding pH, the results showed that the values remained within a nearly neutral range (approximately 6.7–8.9), which is a very suitable range for microbial activity and the biodegradation of both nitrifying and non-nitrifying bacteria. Therefore, there are no inhibitory constraints on biological processes within the treatment system used.

Table 11. TSS result at HRT 6 h

HRT (h)	Influent	EFF (MBBR)	R% (MBBR)	EFF (MBBR + MBR)	R% (MBBR + MBR)
	810	328	59.5	64.8	92
	782	284	63.6	58.23	92.5
	763	259	66.05	57.22	92.4
	754	247	67.2	55.79	92.6
	800	310	61.25	94.4	88.2
	742	230	69	71.23	90.4
6	680	189.48	72.14	62.56	90.8
	736	189.8	74.2	61.82	91.6
	718	175.19	75.6	53.68	92.5
	736	173.69	76.4	52.99	92.8
	726	183.68	74.69	67.52	90.7
	750	173.25	76.9	66	91.2
	746	171.58	77	63.41	91.5
Mean ± SD	749.42 ± 34.71	207.33 ± 47.18	71.60 ± 5.82	64.67 ± 11.11	91.48 ± 1.27

Note: TSS = total suspended solids; HRT = hydraulic retention time; EFF = effluent; MBBR = moving bed biofilm reactor; MBR = membrane bioreactor; SD = standard deviation.

Table12. TSS result at HRT 12 h

HRT (h)	Influent	EFF (MBBR)	R% (MBBR)	EFF (MBBR + MBR)	R% (MBBR + MBR)
	740	280.16	62.14	54.76	92
	716	257.26	64	47.25	93.4
	742	258.22	65.2	48.23	93.5
	640	209.72	67.23	37.05	94.2
	732	229.84	68.6	40.26	94.5
	813	245.52	69.8	42.27	94.8
12	720	205.92	71.4	38.16	94.7
	632	193.89	69.32	32.86	94.8
	735	211.31	71.25	47.04	93.6
	754	196.09	74	45.24	94
	810	199.09	75.42	39.52	95.12
	772	181.42	76.5	37.05	95.2
	714	156.93	78.02	32.13	95.5
Mean ± SD	732.31 ± 52.62	208.26 ± 32.96	69.03 ± 4.88	42.93 ± 7.96	94.42 ± 1.03

Note: TSS = total suspended solids; HRT = hydraulic retention time; EFF = effluent; MBBR = moving bed biofilm reactor; MBR = membrane bioreactor; SD = standard deviation.

Table 13. TSS result at HRT 24 h

HRT (h)	Influent	EFF (MBBR)	R% (MBBR)	EFF (MBBR + MBR)	R% (MBBR + MBR)
	738	229.81	68.8	42.73	94.21
	732	201.3	72.5	31.47	95.7
	758	193.82	74.43	30.32	96
	643	141.46	78	23.14	96.4
	627	127.9	79.6	18.74	97.01
	739	137.3	81.42	17.36	97.65
24	746	116.59	84.37	16.41	97.8
	752	101.21	86.54	18.04	97.6
	717	88.62	87.64	14.34	98
	786	78.6	90.01	12.57	98.4
	774	70.3	90.50	8.88	98.8
	748	58.79	92.14	7.48	99
	763	41.2	94.60	3.81	99.5
Mean ± SD	732.54 ± 46.92	122.07 ± 58.00	83.12 ± 8.08	18.87 ± 10.81	97.39 ± 1.49

Note: TSS = total suspended solids; HRT = hydraulic retention time; EFF = effluent; MBBR = moving bed biofilm reactor; MBR = membrane bioreactor; SD = standard deviation.

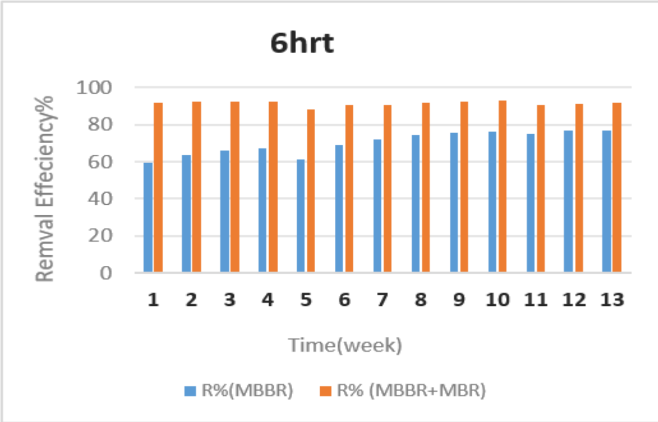


Figure 15. Profile of total suspended solids (TSS) removal rate in hydraulic retention time (HRT) = 6 h

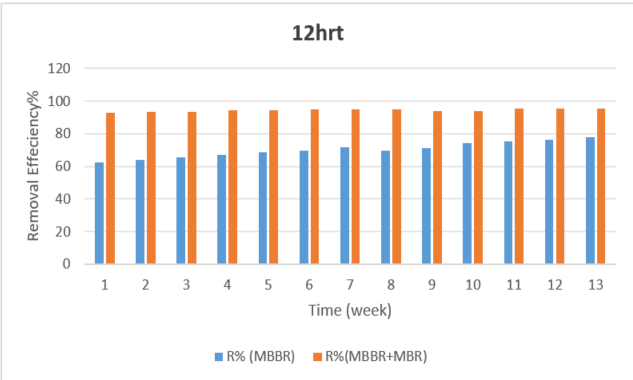


Figure 16. Profile of total suspended solids (TSS) removal rate in hydraulic retention time (HRT) = 12 h

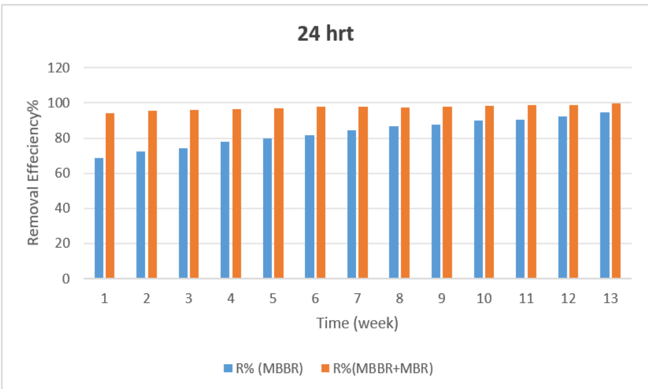
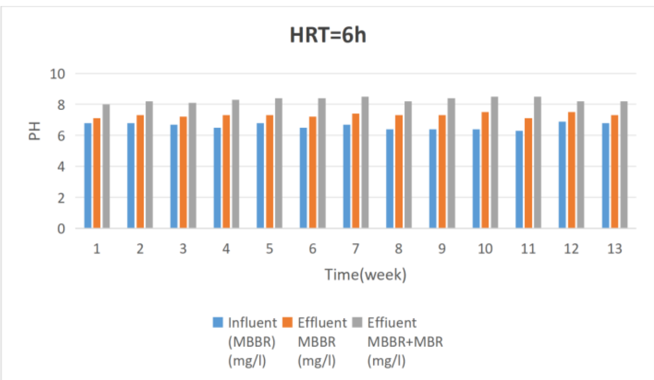


Figure 17. Profile of total suspended solids (TSS) removal rate in hydraulic retention time (HRT) = 24 h



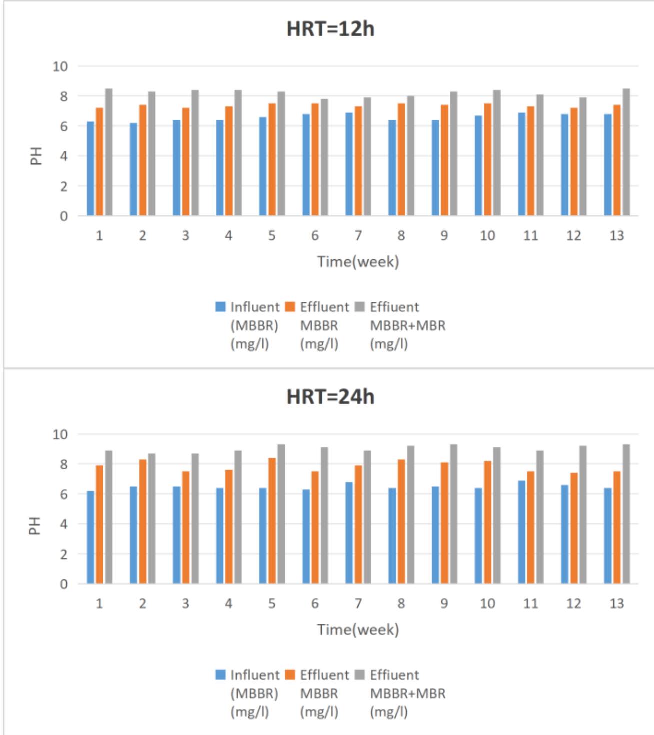


Figure 18. The values of pH at different cycles

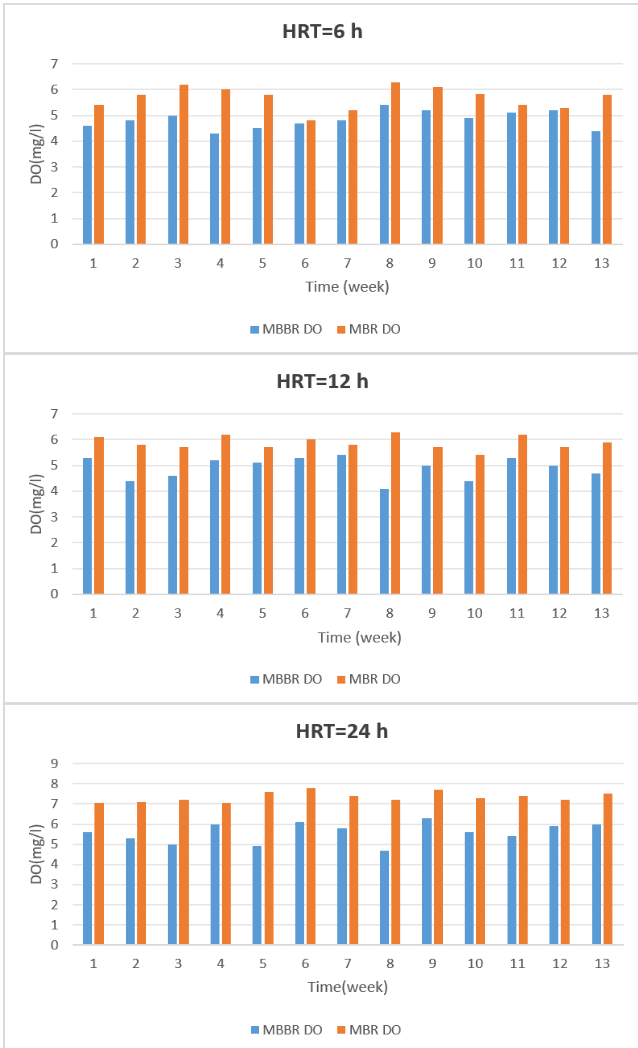


Figure 19. The values of dissolved oxygen (DO) at different cycles

3.1.4 Dissolved oxygen

One important factor is the DO. DO was examined every day. DO levels in this system are kept at 4 mg/L or a little bit higher. Because of their vast surface area and high porosity, sponge carriers are special.

The significance of the oxygen level (4 mg/L): Because of the sponge's deep porous structure, oxygen needs enough partial pressure to enter the pores. The efficiency of aerobic treatment may be decreased if the level drops below this threshold because the sponge's interior may turn anaerobic.

BOD and COD: Because the steady aerobic atmosphere encourages high activity for stabilized bacteria, effective removal of biodegradable organic matter is obtained at this level. In addition to being used for breathing, air is pumped in to clean the hollow fibers' surface and stop fouling, which naturally raises DO levels. As shown in Figure 19.

Impact on BOD and COD: Even complex organic compounds were broken down at the highest rates of COD and BOD elimination. As for DO, it was maintained at a level of 4.3 to 6.3 mg/L during operation, a level sufficient to support aerobic decomposition and biomass activity in the S-MBBR / MBR system. This concentration helped to enhance organic matter oxidation and effectively improve the removal of both COD and BOD, as adequate oxygen availability increases the efficiency of aerobic bacteria and reduces the likelihood of hypoxic conditions within the reactor. The stability of DO at this level also contributed to maintaining relatively stable system performance, which positively impacted the overall removal rates of organic pollutants.

4. CONCLUSIONS

Under optimal operating conditions, the system achieved a COD removal efficiency of 98.16%, a BOD removal efficiency of 95.64%, and a TSS removal efficiency of 99.5%, resulting in final treated water concentrations of COD = 32.11 mg/L, BOD = 32.5 mg/L, and TSS = 3.81 mg/L. These values were within acceptable discharge limits according to relevant environmental standards.

The results confirmed that increasing the HRT improves overall treatment performance; however, the highest efficiency was achieved at the optimal HRT, and no significant improvement was observed beyond this point.

In a three-stage (first, second, and third) poultry slaughter wastewater treatment, an MBBR based on sponge carriers and an MBR. The tests and findings from this stage led to the following conclusions:

1. The moving bed biofilm and MBR system can effectively treat wastewater from poultry slaughter and achieve a high rate of pollutant removal.

2. The findings show that MBBR with the MBR removes pollutants (COD, BOD, and TSS) more effectively than MBBR alone.

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