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Optimizing the MBBR System and Integrating Nanoparticles to Improve Wastewater Treatment Efficiency

Ahmed Eid[1*], Abd-Elaziz El-sayed[2], Mohamed Ayoub[2], Ahmed El-Morsy[2]

[1] M.Sc Student, Public Works Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt
[2] Public Works Engineering Department, Faculty of Engineering, Tanta University, Tanta, 31511, Egypt
* Corresponding author's e-mail: ahmed152570@f-eng.tanta.edu.eg

ABSTRACT

Wastewater treatment faces a growing challenge in removing nutrients and organic matter. This study aimed to evaluate the effectiveness of the moving bed biofilm reactor (MBBR) system in removing nutrients and organic from municipal wastewater. The impact of different carrier filling ratios and hydraulic retention times (HRT) on the removal efficiency was systematically investigated. Moreover, the addition of nanoparticle additives to enhance system performance was evaluated. The optimal conditions for the MBBR system were 30–45% filling ratios and a 10-hour HRT, resulting in maximum removal efficiencies for biological oxygen demand (BOD_5), chemical oxygen demand (COD) and ammonia (NH_4^+-N) with a percentage of 85.23%, 81.69%, and 54.45% respectively. Furthermore, adding nanoparticles improved the BOD_5 and COD removal efficiencies by 6.6% and 8.0% respectively, compared to the MBBR system without nanoparticles.

Keywords: moving bed biofilm reactor, nanoparticles, wastewater treatment, filling ratio, hydraulic retention time.

INTRODUCTION

Moving bed biofilm systems have gained significant attention for treating various types of wastewater. In MBBR, carriers are added for forming and growing biofilm, known as attached biomass, while suspended biomass is utilized similarly to conventional activated sludge (Santos et al., 2020; Qiqi & Ibrahim, 2012). The biomass concentration typically ranges from 3 to 4 kg ss/m^3, while the attached biomass on the carriers can reach 10000–12000 mg/L. The high biomass concentration leads to a high volumetric removal rate, making MBBR a more suitable process. This sustainability, along with stable microorganism concentration and high volumetric rate, allows for reduced reactor volume, making MBBR a versatile treatment technology (Bhattacharya, 2022; Ødegaard, 1999). The carrier media in MBBR have less clogging and low head loss due to agitation during aeration. Unlike activated sludge systems, MBBR does not require sludge recycling, saving effort in excess biomass removal (Madan et al., 2022; Ødegaard, 1999). MBBR has proven to be superior to surface aeration systems in reducing contamination and pollution load, making it a strong alternative for treating various types of wastewater, including industrial wastewater, such as dairy (Santos et al., 2020), laundry (Bering et al., 2018), pulp, paper (Vaidhegi, 2013), and pharmaceutical wastewater (Brinkley et al., 2007).

Considering the MBBR system advantages, some operation conditions affect their performance. One of the most important operation conditions is the carrier filling ratio which produces the amount of surface area available for biofilm growth and is considered a critical factor for the removal of pollutants in the MBBR system (Zhao, Liu, et al., 2019). Typically, MBBR performance depends on a filling percentage of about 60% to 70% of the empty reactor (Leiknes & Ødegaard, 2001). However, a high filling percentage can reduce efficiency due to mixing issues and carrier discrepancies, leading to a lack of biofilm formation on the outer surface of the carriers. Therefore, the inner specific surface area is crucial for design components (Weiss et al., 2005). The shape and size of carrier media also impact biomass growth, depending on the effective specific area per unit reactor volume. Moreover, the other important operation condition is to determine the optimal hydraulic retention time (HRT) which refers to the duration required for wastewater to flow through a bioreactor, allowing for the thorough removal of organic matter and nutrients. HRT significantly impacts the cost of constructing and operating wastewater treatment plants. The design of the MBBR system depends on the wastewater properties, available surface area for biofilm growth, and effluent biodegradability, which must meet standard discharge regulations.

Di Trapani et al. (2008) conducted a pilot plant study to evaluate the system of a hybrid moving bed biofilm reactor (HMBBR) in enhancing the performance of existing wastewater treatment facilities without expanding the plant footprint. The obtained results showed that a filling ratio of 35% resulted in higher removal efficiency for COD and TSS compared to 66% due to suspended growth concentration at 35% filling ratio was higher. Conversely, the removal efficiency of NH_4^+-N was higher at 66% due to an increase in carriers containing attached biomass and nitrifying bacteria. On the other hand, Gu et al. (2014) conducted a study to demonstrate how the filling ratio of carriers affects the efficiency of removing COD, thiocyanate, phenol, and ammonia from coking wastewater using MBBR, at a hydraulic retention time (HRT) of 20 hours. The experiment involved varying the filling ratio from 20% to 60%. The results indicated that a 50% filling ratio resulted in the highest removal efficiency for COD, phenol, and thiocyanate, with percentages of 99%, 89%, and 99% respectively.

Martín-Pascual et al. (2016) conducted research on the MBBR system, focusing on determining the optimal HRT, temperature, and carrier filling ratio for effectively removing BOD_5, COD, and NH_4^+-N from urban wastewater. Their study utilized K1 AnoxKaldnes as the carrier, with filling ratios of 20%, 35%, and 50%, and HRTs of 10 and 24 hours. The study found that the highest removal efficiencies for BOD_5, COD, and NH_4^+-N occurred at a 35% filling ratio and 24 hours of HRT. Additionally, the study demonstrated an 86% removal of COD and a 91% removal of BOD_5. Moreover, Majid & Mahna, (2019) built a pilot scale MBBR to analyze the impact of HRT, temperature, and high organic loading rate on the efficiency of MBBR for treating industrial wastewater. K3 Kaldnes was used as the carrier. The HRTs tested were 3, 5, 8, and 12 hours. Results showed that at 12 hours of HRT, COD and BOD_5 effluents were the lowest under a constant COD and BOD_5 loading rate of 1000 mg/L and 490 mg/L respectively. The COD and BOD_5 removal efficiencies at 12 hours of HRT were 87% and 75%, while at 8 hours of HRT, removal efficiencies were 84% and 71% respectively. Although 12 hours of HRT was more efficient than 8 hours of HRT in terms of COD and BOD_5 removal, it was recommended to use 8 hours of HRT as the optimum due to a slight difference and to shorten the treatment process.

Tadda et al., (2021) conducted research on a lab-scale MBBR system to investigate the effect of Saddle-Chips (SC) biocarriers compared with Kaldnes K5 for treating mariculture wastewater in terms of NH_4^+-N removal. The experiment was conducted under conditions of 12-24 HRT and a 30%-60% filling ratio. The result showed that nutrient removal efficiency was higher at 60% of filling ratio and 24 hours of HRT. In a study by Bakar et al., (2020) the performance of a lab-scale MBBR system was investigated for the treatment of palm oil mill effluent (POME) at different hydraulic retention times (HRTs) of 24, 48, and 72 and different filling ratios of 25%, 50%, and 70%. The results indicated that the removal efficiency of COD and NH_3-N increased along with HRT, while the best removal efficiency was achieved at 50% of filling ratio.

Nanoparticles are extremely small materials ranging in size from 1 to 100 nm. Nanotechnology involves the study and application of nanoscale materials, which exhibit unique characteristics and functionality due to their tiny dimensions with large surface area (Kunhikrishnan et al., 2015; Keller et al., 2013). Nano-materials offer advantages such as high reaction activity, functionalization, specific surface area, and size-dependent properties, making them suitable for applications like wastewater treatment and water purification. Metal oxide nanoparticles are easy to reuse, offer more adsorption sites, have a high specific surface area, and may be compressed without significantly reducing their surface area. Some also exhibit super paramagnetic properties, surpassing activated carbon in terms of adsorption performance (Corsi et al., 2018). In this manner, Youssef et al., (2020) explained the impact of nanoparticles on greywater treatment by carrying out a laboratory scale of a sequencing batch reactor (SBR) system with the addition of nanoparticles consisting of CaO (35-40%), Al_2O_3 (40-45%), Fe_2O_3 (5-15%) and SiO_2 (2-3%) with a dose of 4 mg/L. The authors showed that by using SBR with nanoparticles addition and HRT of 12 hours, the overall removal of organic and nutrient from greywater was 86.71%, while the removal efficiency of organic and nutrient without the addition of nanoparticles under the same conditions was 54.2%, with an increase of about 32.51%, so they recommended the usage of INNPT additives in the treatment of greywater.

Ali et al., (2021) also proved the efficiency of nanoparticles by conducting research on an MBBR system with nanoparticles (INNPT) additives for the treatment of leachate wastewater. The results showed that the BOD_5, COD, TSS, NH_3-N, TKN, and TP removal efficiencies were 99.42%, 98.89%, 99.47%, 97.64%, 99.79%, and 75.86% respectively. The efficiency increase was due to the coagulation that occurred in the reactor between suspended solids and colloidal matters and also the very large specific surface area of the powder additives led to a higher action rate. On the other hand, Tan et al., (2015) conducted a study on a lab scale MBR system operated with ZnO nanoparticles with different concentrations. The study investigated the impact of ZnO nanoparticles on the properties of activated sludge, membrane fouling, and bacterial community. The authors found that after a long time of usage of ZnO nanoparticles with the system, removal efficiency of COD and nitrogen decreased with the addition of ZnO nanoparticles, it has also a significant impact on activated sludge properties lead to increase of membrane fouling.

Most of the past studies on MBBR systems have investigated wastewater treatment. However, none have investigated the ability of MBBR to treat domestic wastewater with the addition of nanoparticles. Hence, this study aimed to optimize the MBBR system performance by conducting laboratory experiments on carrier filling ratio and HRT to enhance its operation and also aimed to investigate the impact of nanoparticle additives on the MBBR system performance.

MATERIALS AND METHODS

Study area

The experiments were carried out in Abo Dawood wastewater treatment plant (WWTP). The location of the WWTP is Abo Dawood, Temai Al Amdeed, Dakahlya Governorate, Egypt. This plant as shown in Figure (1), is belonged to Ministry of Housing, Utilities and Urban Communities-Water and Wastewater Company. Table 1 represents the quality of the wastewater, collected for implementing the experimental

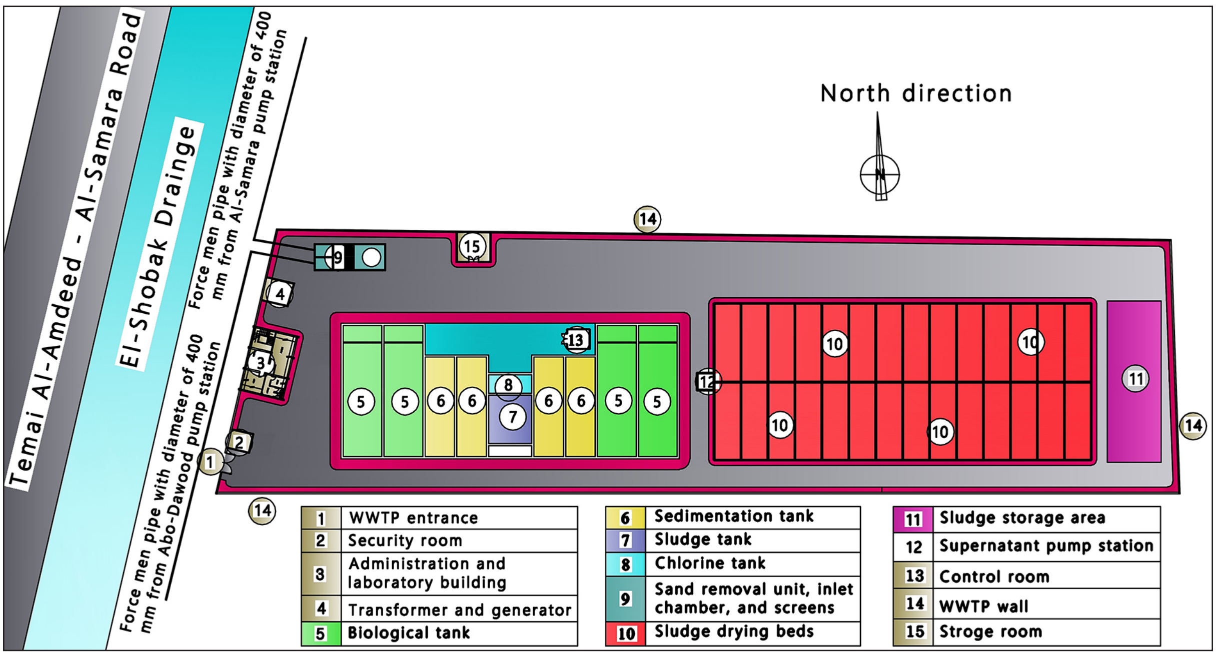

Figure 1. Layout of Abo Dawood WWTP

Table 1. Characteristics of the influent wastewater to the experiments

Parameter	Influent to the experiments (Mean ± SD)	Limits for final effluent*
BOD_5 (mg/L)	214.05 ± 14.21	≤60
COD (mg/L)	332.86 ± 21.66	≤80
NH_4^+-N (mg/L)	55.00 ± 8.32	-
pH	7.5 ± 0.5	6.5–8.5

Notes: *Adapted from Metcalf and Eddy (2007).

program. Tests were conducted at Abo Dawood WWTP Laboratory using the Standard Methods (2017) for Water and Wastewater Examination, 23rd edition, as prepared and published by APHA, AWWA, and WEF in 2017.

The experimental setup

The experimental wastewater treatment system includes a wastewater source tank, a biological reactor of the MBBR system, and a sedimentation tank as depicted in Figure 2. The wastewater source tank, made of glass measuring 50×50×50 cm, supplies wastewater to the biological reactor through a hand valve without a pump. The reactor employs a gravity-dependent flow rate variation, allowing for controlled flow rates. Periodic flushing of the MBBR inlet line is necessary to remove biofilm and accumulated solids, ensuring continuous wastewater flow. The biological reactor of MBBR used in the experiment measures 30×30×40 cm with an effective volume of 20 liters and consists of:

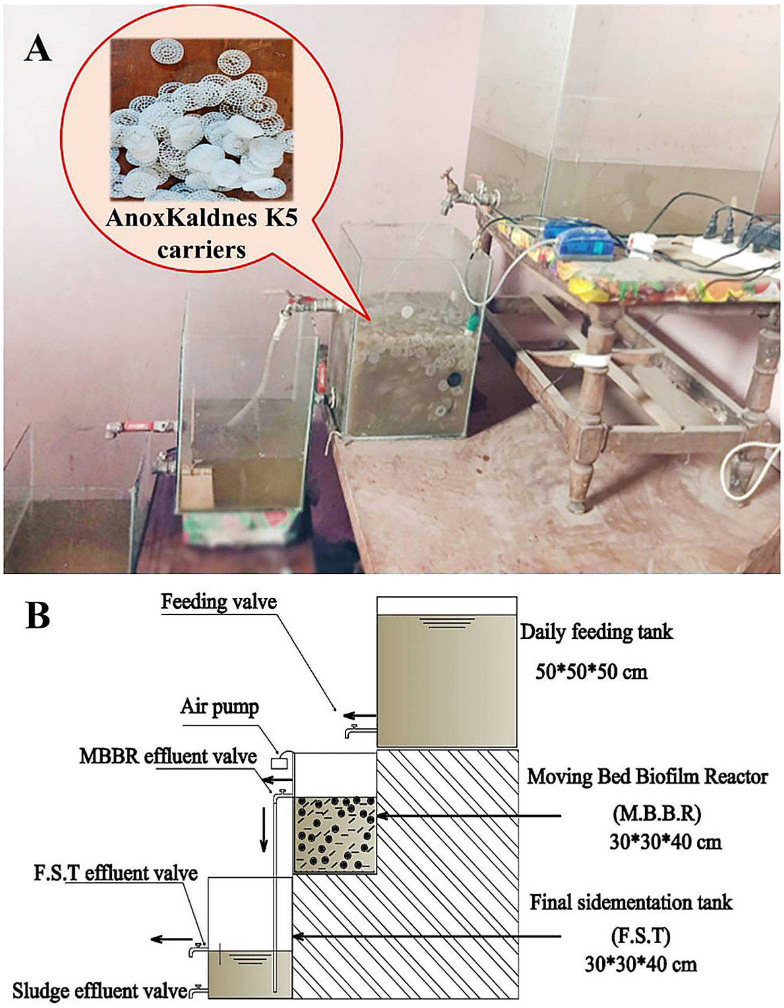

Figure 2. Experimental setup of MBBR system followed by settling tank in (a) a photo image, (b) a schematic diagram

- An aeration system including air pump which operates with a rate of approximately 2.0 liters per minute and a manifold connected to a vertical pipe that rises above the liquid level in the reactor to prevent liquid from flowing to the air pump when it is turned off. It produces coarse bubbles to keep the Kaldnes media in suspension and circulation. Aeration is crucial for microbial growth, stability on the carriers, and movement throughout the reactor. It supplies oxygen for microbial oxidation and enhances the turbulent intensity of the fluid, which is essential for efficient wastewater treatment (Li et al., 2011).
- The experiment used AnoxKaldnes K5 as the biological carrier, which consists of circular ships with a 25 mm diameter and 4 mm height. These carriers have 64 smaller dividers where microorganisms can attach and grow. The carrier has a density of 0.95 gm/cm^3, it is slightly lighter than water, and has a protected surface area of 800 m^2/m^3 for biofilm growth (Mozia et al., 2020). More information about the carriers is available in Table (2), and their form is shown in Figure (2-a).

The sedimentation tank was 30×30×40 cm in size, with an effective volume of 10 liters and an effective height of 11 cm. It is utilized for physically separating sludge generated in the biological reactor from treated water through sedimentation.

Nano Tech, Egypt imported nanoparticles (INNPT nanomaterial) with a composition of CaO (35-40%), Al_2O_3 (40-45%), Fe_2O_3 (5-15%) and SiO_2 (2-3%) by weight were used. The nanoparticles are in powder form and were added at a dosage of 4 mg/L at the start of the MBBR cycle (El-Hefny et al., 2018; Youssef et al., 2020).

The MBBR system was studied to assess the impact of carrier filling ratio and hydraulic retention time on removing organics and nutrients. Subsequently, the system performance was evaluated with the addition of nanoparticles. The first phase involved varying the filling ratio of carriers from 60% to 15% in the reactor, with an 8-hour HRT and aeration rate of 2.0 L/minute. The second phase investigated the effect of HRT (6, 8, and 10 hours) on organic and nutrient removal while maintaining a 30% filling ratio and 2.0 L/min aeration rate. The final phase focused on studying the MBBR system by adding nanoparticles at a dosage of 4 mg/L under a 30% filling ratio, 8-hour HRT, and 2.0 L/min aeration rate.

Table 2. Characteristics of AnoxKaldnes K5 carriers

Type	AnoxKaldnes K5
Material	Polyethylene
Shape	cylinder
Density	0.95 gm/cm^3
Diameter	25 mm
Height	4 mm
Specific Biofilm surface area m^2/m	800 m^2/m^3

RESULTS AND DISCUSSION

Carrier filling ratio effect on organic and nutrient removal from wastewater

The study examined four different carrier filling ratios (15%, 30%, 45%, and 60%) for treating municipal wastewater. According to the findings in Figure (3), the highest BOD_5 removal occurred at 30% to 45% filling ratio. At 15% filling ratio, the MBBR system removed 81.5% of BOD_5, which increased to 83.0% and 82.3% at 30% and 45% filling ratios, respectively. However, BOD_5 removal decreased to 80.7% at 60% filling ratio. Additionally, the highest COD removal efficiency was observed at a filling ratio of 30% to 45%, as depicted in Figure (4). The COD removal efficiencies at filling ratios of 15%, 30%, 45%, and 60% were 76%, 78.5%, 78.0%, and 76.3% respectively. In conclusion, the optimal organic removal percentage was achieved at a 30%-45% filling ratio for municipal wastewater treatment.

Figure (5) illustrates the NH_4^+-N removal efficiency at various filling ratios. The removal efficiency of NH_4^+-N at different filling ratios closely resembled that of COD. Specifically, the percentage removal at filling ratios of 15%, 30%, 45%, and 60% were 41.4%, 46.0%, 50.7%, and 45.0% respectively. The decline in organic and nutrient removal efficiency at a 60% filling ratio was attributed to the slower movement of carriers in the reactor, caused by a greater number of carriers. This resulted in reduced mixing efficiency and the formation of a thick layer of biomass on the carriers, impeding the permeation of organic matter and dissolved oxygen. Conversely, at a 15% filling ratio, carriers moved more rapidly, leading to the detachment of microorganisms. In contrast, filling ratios of 30% to 45% facilitated uniform carrier movement with fewer collision issues, creating favorable conditions for microorganisms to adsorb organic matter and dissolved oxygen

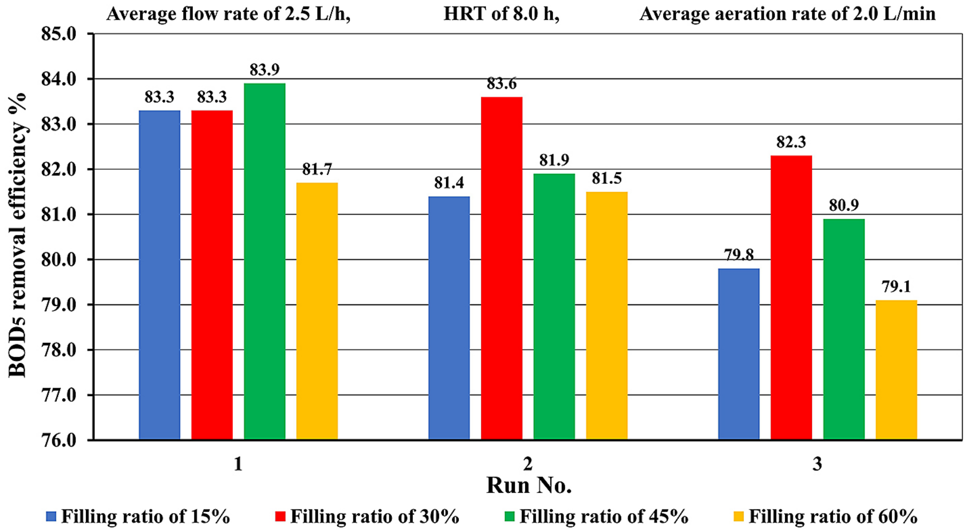

Figure 3. BOD_5 removal efficiency at different filling ratios

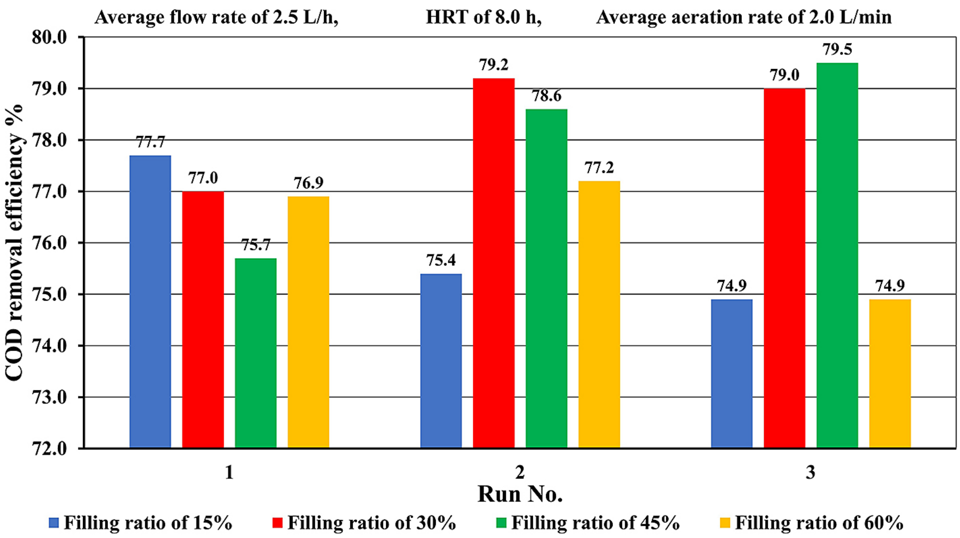

Figure 4. COD removal efficiency at different filling ratios

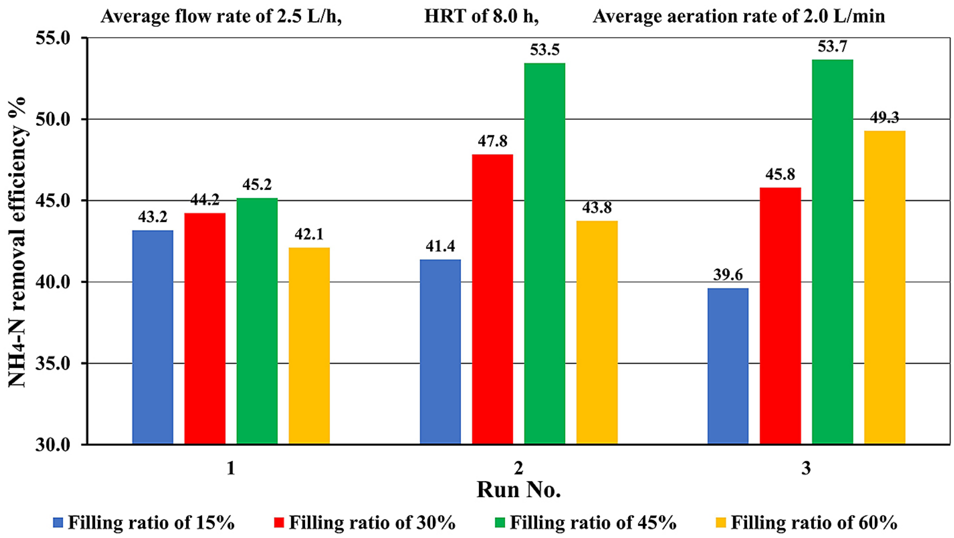

Figure 5. NH_4^+-N removal efficiency at different filling ratios

from the wastewater, inhibit microorganism loss, and enhance biofilm formation, thereby improving organic and nutrient removal.

The study findings align with those of Martín-Pascual et al. (2016), who reported that the optimal removal efficiencies for BOD_5, COD, and NH_4^+-N occurred at a 35% filling ratio. Similarly, Bakar et al. (2020) also concluded that a 50% filling ratio resulted in the best removal efficiency for COD and NH_4^+-N. However, the results differ from those of Shrestha (2013), who found that a 20% filling ratio yielded the best removal efficiency. Additionally, Di Trapani et al. (2008) observed that a 35% filling ratio was optimal for COD removal, while Zhang et al. (2016) found no significant difference in removal efficiency at different filling ratios for TOC and NH_4^+-N. Furthermore, the study results align with Feng et al. (2012) in that filling ratio had little impact on COD removal, but NH_4^+-N removal efficiency was significantly higher at 40% filling ratio than at 20%. However, results did not match Zhao et al. (2019), who found that increasing filling ratio led to increased COD removal efficiency, and NH_4^+-N removal efficiency was highest at 30–40% filling ratios. These findings are similar to Barwal & Chaudhary (2015) research, which showed that a 40% carrier filling ratio for treating synthetic municipal wastewater was optimal. The appropriate filling fraction allowed for the growth of autotrophic nitrifying bacteria on the biofilms attached to carriers. The large spaces between carriers facilitated the contact between solid, gas, and liquid elements, increasing mass transfer area and rate, and ultimately leading to higher microbial growth (Nicolella et al., 2000).

Hydraulic retention time effect on organic and nutrient removal from wastewater

In this study, comparing hydraulic retention times (HRTs) of 6, 8, and 10 hours showed that increasing the HRT led to improved efficiency in removing organic matter and nutrients. The removal efficiency of BOD_5 increased from 80.0% at 6 hours HRT to 85.2% at 10 hours HRT, as depicted in Figure (6). Similarly, the COD removal efficiency increased from 76.3% to 81.7% with the corresponding HRTs, shown in Figure (7). NH_4^+-N removal also improved from 42.4% to 54.3% with the increase in HRT, as illustrated in Figure (8). HRT had a significant impact on organic and nutrient removal by carriers, as it affected the organic load and provided sufficient time for microorganisms to adsorb organic matters and dissolved oxygen from the wastewater. A longer HRT of 10 hours demonstrated the highest removal efficiency, while 6- and 8-hour HRTs also yielded good results within the limits of Egyptian environmental law (Egyptian Government, 1982). The cost considerations favor a 6-hour HRT.

The research results are similar to those of previous studies. Golestani et al. (2021) observed an increase in the COD removal efficiency with longer hydraulic retention time. Similarly, Martín-Pascual et al. (2016) found optimal BOD_5 and COD removal at a 24-hour HRT. Bakar et al. (2020) also noted an increased removal efficiency with longer HRT. In contrast, Shrestha (2013) found that attached the biomass concentration increased with higher organic loading rates, leading to improved organic and nutrient removal as HRT decreased.

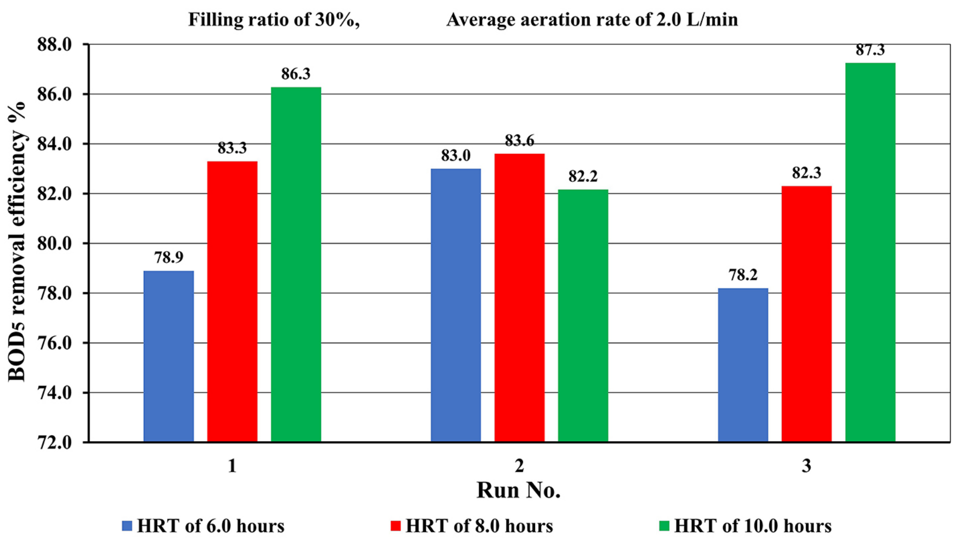

Figure 6. BOD_5 removal efficiency at different HRTs

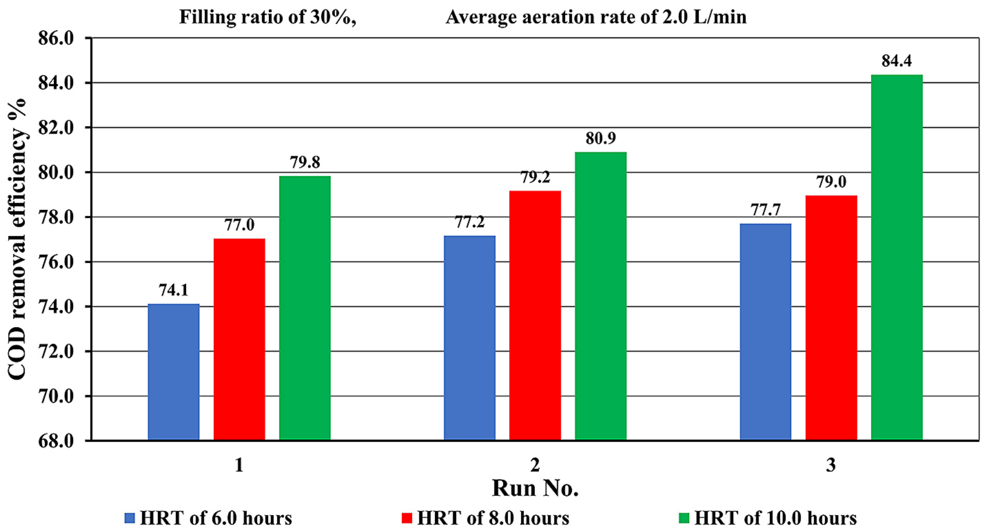

Figure 7. COD removal efficiency at different HRTs

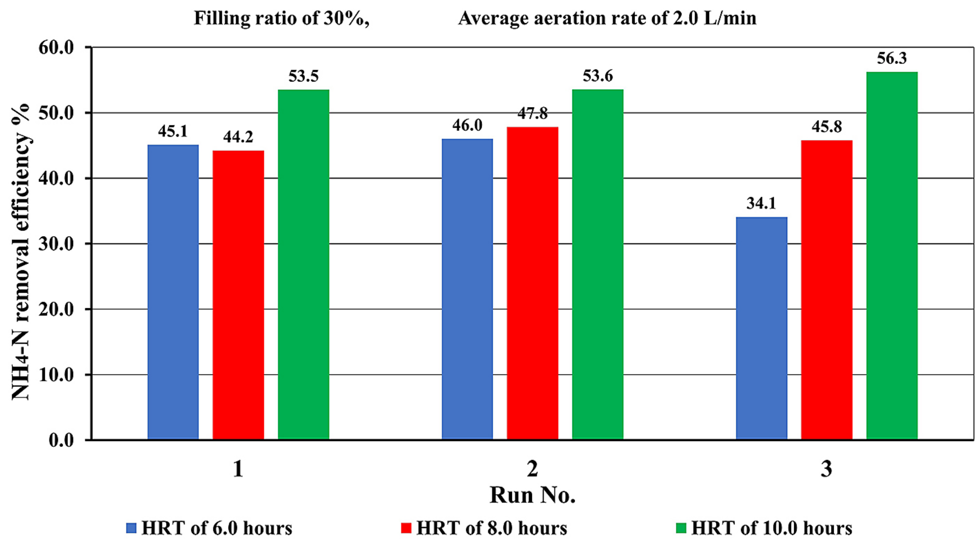

Figure 8. NH_4^+-N removal efficiency at different HRTs

Effect of nanoparticles additives on organic and nutrient removal from wastewater

Figures 9, 10, and 11 illustrate the average effluent concentrations of BOD_5, COD, and NH_4^+-N in MBBR with and without nanoparticle additives. The removal efficiencies for the MBBR without nanoparticles were 83.0%, 78.4%, and 45.9% for BOD_5, COD, and NH_4^+-N, respectively, resulting in an effluent of 36.3, 72.7, and 27.3 mg/L. However, the addition of nanoparticles improved the removal efficiencies to 89.7%, 86.3%, and 45.8%, respectively, with an effluent of 22.3, 46.0, and 30.7 mg/L. The results indicate that the INNPT additives increase the organic removal efficiency by coagulating the colloidal materials and suspended solids inside the reactor. The powder form of the additive has a large active specific area, which increases the rate of action and shortens the interparticle diffusion distance, leading to increased adsorbent surface utilization and assurance of mass transfer. The addition of the additive inside the MBBR reactor with aeration and mixing makes it more efficient (Zaidi et al., 2015; Ali et al., 2021). However, the treatment results were lower than expected, possibly because the aeration rate was lower than the recommended rate of 4.5 L/min, according to Shresta (2013).

Abdul-Majeed et al. (2012) reported 80% BOD_5 removal efficiency and was lower than that achieved by Mizeel et al. (2015) at 88%. However, with the addition of INPPT additives, the BOD_5 effluent of MBBR was higher than the results of Mizeel et al. (2015). This indicates the effectiveness of MBBR with nanoparticles in BOD_5 removal compared to the use of three

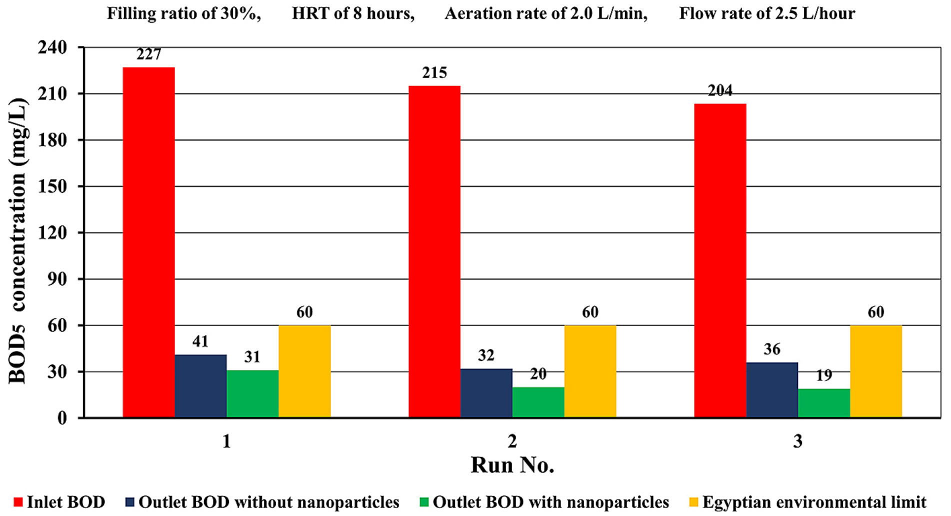

Figure 9. Inlet and outlet BOD_5 concentration of MBBR with and without nanoparticles compared with Egyptian environmental low limits of low 48 for year 1982

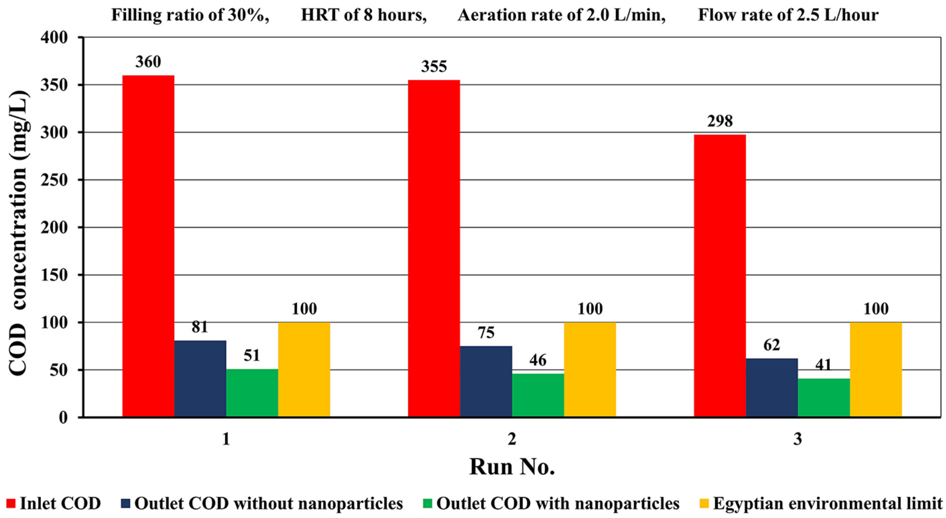

Figure 10. Inlet and outlet COD concentration of MBBR with and without nanoparticles compared with Egyptian environmental low limits of low 48 for year 1982

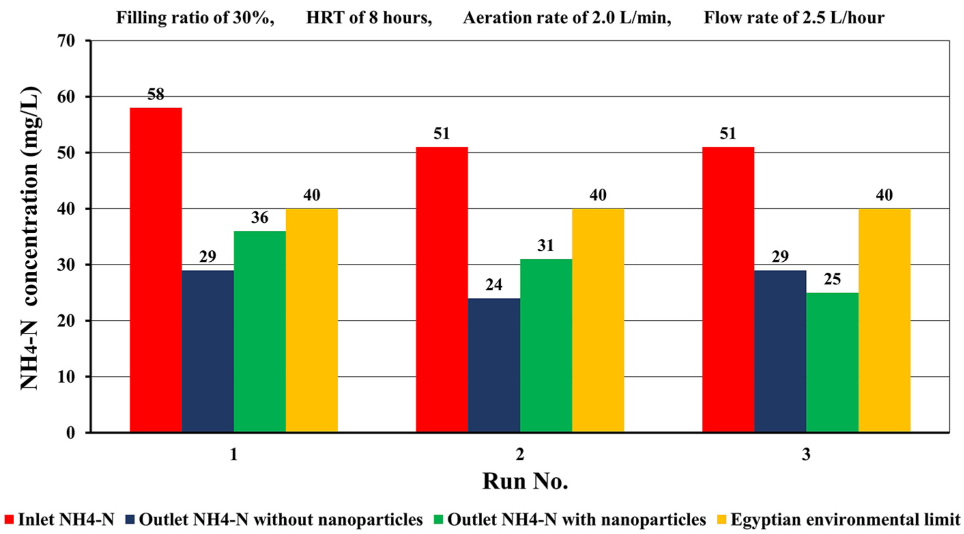

Figure 11. Inlet and outlet NH_4^+-N concentration of MBBR with and without nanoparticles compared with Egyptian environmental low limits of low 48 for year 1982

reactors in series followed by flocculation chamber, final clarifier, and drum filter. Additionally, the COD removal efficiency in the MBBR with INPPT additives is comparable to that reported by Pratiwi et al. (2018) at 89%. Ozone pretreatment was used to improve the treatment of industrial textile wastewater in the MBBR, highlighting the efficiency of INNPT additives in a single MBBR tank compared to ozone pretreatment with longer HRT. However, there was no improvement in the removal of NH_4^+-N in the MBR system with INPPT additives, possibly due to insufficient time for nanoparticle addition.

CONCLUSIONS

This study aimed to optimize the MBBR operational conditions to remove nutrients and organic substances, as well as assess the impact of adding nanoparticles to the system. Results showed that a filling ratio of 30-45% was optimal for BOD_5 and COD removal efficiency, while a 45% filling ratio was most effective for NH_4^+-N removal efficiency. The recommended filling ratio for domestic wastewater treatment is within this range. The optimum HRT for BOD_5, COD, and NH_4^+-N removal efficiency was found to be 10 hours, with maximum removal efficiencies of 85.23%, 81.69%, and 54.45% respectively. Additionally, adding nanoparticles improved BOD_5 and COD removal efficiencies by 6.6% and 8.0% respectively, compared to the MBBR system without nanoparticles.

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