

EFFECT OF HYDRAULIC RETENTION TIME ON FOOD CHAIN REACTOR (FCR) PERFORMANCE IN INDUSTRIAL WASTEWATER TREATMENT

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Abstract

Industrial estate wastewater treatment presents significant challenges due to its complex composition. Food Chain Reactor (FCR) technology has been implemented in several wastewater treatment plants (WWTPs) in industrial estates across Indonesia as a promising solution for the removal of organic compounds, nutrients, and heavy metals. However, there is limited research on the optimization of FCR performance. This study aims to evaluate the optimal hydraulic retention time (HRT) for FCR by assessing its efficiency in removing COD, ammonia, phosphate, and nickel from industrial estate wastewater. A 60 L lab-scale FCR reactor was tested under HRT variations of 12, 16, and 24 hours. The pollutant removal efficiencies ranged from 86.16% to 90.79% for COD, 77.92% to 88.96% for ammonia, 54.76% to 63.09% for phosphate, and 40.83% to 51.99% for nickel. The 12-hour HRT achieved the highest COD removal efficiency ($90.79\% \pm 1.59\%$), while the variation in HRT had minimal influence on ammonia, phosphate, and nickel removal. ANOVA results confirmed a highly significant effect of HRT on COD removal ($p < 0.0001$), while the removal efficiencies for ammonia, phosphate, and nickel were not significantly affected ($p > 0.05$). These findings suggest that FCR technology is highly effective for COD removal at shorter HRTs, but further optimization is needed for more efficient removal of nutrients and heavy metals.

Keywords: Food Chain Reactor, hydraulic retention time, industrial wastewater treatment, COD removal, phosphorus removal, nickel removal, ANOVA.

Introduction

To address the increasing demand for industrial development, industrial estates are designated areas planned as centers for industrial activities. These estates contribute significantly to Indonesia's economic growth by attracting investment and generating employment (Berawi et al., 2019). However, managing wastewater from industrial estates remains a major environmental challenge due to its complex composition, which includes a diverse range of high-concentration pollutants that are often difficult to degrade (Arora et al., 2017; Suresh et al., 2023).

Industrial estate wastewater is typically treated using physicochemical or biological processes. Physicochemical treatments, such as advanced oxidation processes (AOPs) and membrane technologies, are commonly applied (Chang et al., 2007; Naguib et al., 2022). AOPs efficiently break down non-degradable organic compounds and toxic pollutants (Pandis et al., 2022), while membrane technologies, including reverse osmosis (RO), nanofiltration (NF), and electrodialysis, effectively remove dissolved solids (Daniels, 2005). However, both methods have significant drawbacks, including high

operational costs and process complexity, making them less viable for widespread application (Dhamorikar et al., 2024; Gautam et al., 2022).

In contrast, biological treatment is more cost-effective and environmentally sustainable, making it a widely adopted option for industrial wastewater treatment (Bui et al., 2022). The most commonly used biological processes include activated sludge-based technologies, bioaugmentation processes, and microalgae-based treatment (Nagda et al., 2022; Sinharoy & Singh, 2022). Among these, modified activated sludge technology, such as attached growth activated sludge, is one of the most widely used alternatives for industrial estate wastewater treatment (Waqas et al., 2023). However, a key limitation of the activated sludge process is its inefficiency in removing heavy metals and treating high organic pollutant loads (Wen et al., 2016).

To overcome these challenges, Food Chain Reactor (FCR) technology was developed as an innovative solution for industrial wastewater treatment, particularly for heavy metal removal. Introduced by ORGANICA in 2015, FCR integrates Integrated Fixed-Film Activated Sludge (IFAS) technology with constructed wetlands (CW), creating a hybrid treatment system that enhances pollutant removal efficiency (Engel, 2016). The combination of suspended and attached microbial communities enables the reactor to withstand shock loads and effectively degrade high concentrations of organic pollutants. Additionally, plant roots extending into the reactor media facilitate nutrient and heavy metal uptake, further improving treatment performance. Compared to conventional suspended-growth activated sludge systems, FCR offers multiple advantages, including a smaller footprint, lower energy consumption, reduced carbon emissions, and minimal sludge production, thereby reducing the need for complex sludge management (Engel, 2016; Sari & Rifai, 2020).

Despite its promising potential, research on FCR and IFAS technology to treat industrial estate wastewater remains limited. A study by Li et al., (2012) reported that IFAS demonstrated effective chemical oxygen demand (COD) and $\text{NH}_4\text{-N}$ removal efficiencies of 74% and 93%, respectively, in industrial wastewater treatment. In domestic wastewater treatment, IFAS has been shown to support simultaneous nitrification and denitrification (SND), with removal efficiencies of 88.51% for SND and 82.78% for total nitrogen (TN) at a dissolved oxygen concentration of 0.5 mg/L (Jin et al., 2023). Another study reported 81% total phosphorus (TP) removal efficiency using IFAS for municipal wastewater treatment (Yang Bai et al., 2016). These findings highlight the potential of IFAS-based technology in treating complex industrial estate wastewater. As an integral part of FCR technology, constructed wetlands (CW) have also demonstrated high efficiency in heavy metal removal from industrial wastewater. Khan et al. (2009) found that CW achieved removal efficiencies of 91.9% for Cd, 74.1% for Fe, 40.9% for Ni, and 89% for Cr. Another study by Gill et al. (2014) reported that CWs could achieve 60–80% removal efficiency for Cu, Zn, and Pb from stormwater. The integration of IFAS and CW in FCR technology is therefore expected to achieve high simultaneous removal efficiencies for COD, nutrients, and heavy metals.

Further research on FCR technology is needed to optimize its operational conditions, particularly hydraulic retention time (HRT), to enhance its performance in industrial wastewater treatment. This study aims to analyze the optimal HRT for FCR technology by evaluating its efficiency in the removal of COD, nitrogen, phosphorus, and nickel from industrial estate wastewater (C. Li et al., 2012) (Khan et al., 2009)(Gill et al., 2014)

Research Methods

The Operational Condition of FCR process

A 60 L lab-scale FCR reactor with dimensions $120 \times 20 \times 25$ cm was used in this experiment (Figure 1). The total working volume of the reactor was 40.25 L, with a media volume of 20.25 L. The reactor contained biomodules with a total mass of 290 g and a surface area specification of 154 g/cm^2 , which was used to calculate the total media surface area.

Two 80 L containers were placed at the beginning and end of the reactor system to serve as influent and effluent storage tanks. The experimental wastewater was sourced from raw industrial estate wastewater collected from Jababeka Industrial Park, Cikarang, Bekasi Regency, West Java, Indonesia. The wastewater was continuously pumped into the FCR series using a peristaltic pump from the influent tank, while stirring and aeration were provided via an aerator to maintain aerobic conditions.

The flow between each FCR reactor stage (R1–R6) and to the effluent container occurred by gravity, facilitated by a baffle system placed between reactor stages. Within the FCR reactor, a *Philodendron hastatum* plant was positioned at the center and supported by the reactor structure. The reactor itself was constructed from glass material. A real image of the reactor setup is shown in Figure 2.

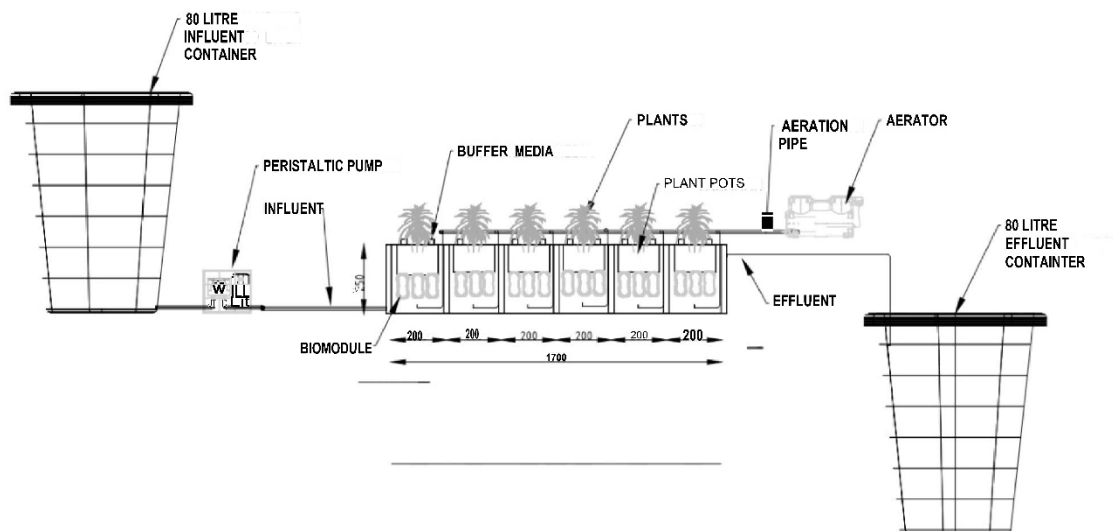


Figure 1. Schematic drawing of the FCR reactor set up



Figure 2. Real picture of FCR reactor set up

Chemical Analysis

During the operation of the FCR reactor, liquid samples were collected at each HRT interval from the inlet, each reactor stage (R1–R6), and the effluent tank. Before analysis, all samples were filtered through a 0.45 µm membrane filter.

The COD concentration was determined using the APHA Standard Method 5540C. Nickel concentration was analyzed using APHA Standard Method 3111B, measured with an atomic absorption spectrophotometer (Shimadzu AA-7000) after sample digestion following APHA Standard Method 3030C (APHA/AWWA/WEF, 2017). The ammonia and phosphate concentrations were measured according to the Indonesian National Standards (SNI) No. 06-6876-2006 and 7815:2009, respectively.

The collected data were plotted and statistically analyzed using ANOVA in Origin 2024 to assess the impact of HRT on pollutant removal efficiency.

Result and Discussion

FCR Performance

The FCR reactor was operated for 51 days, which included 10 days of seeding, 18 days of acclimation, and 23 days of experimental running. After the acclimation period, the reactor was tested at HRTs of 12, 16, and 24 hours, with each HRT condition being applied for at least five cycles.

COD Removal

Figure 3 illustrates the COD removal performance of the FCR system treating real industrial estate wastewater. During the 12-hour HRT operation, the average influent and effluent COD concentrations were $677.8 \text{ mg/L} \pm 24.5 \text{ mg/L}$ and $62.6 \text{ mg/L} \pm 12.68 \text{ mg/L}$, respectively. The corresponding Surface Area Loading Rate (SALR) was approximately $10.75 \text{ g/m}^2/\text{day}$. The final effluent met the national discharge standard for industrial estate wastewater treatment plants as regulated by PermenLH No. 3/2010. Notably, COD concentrations in the effluent had already met the standard at R5 of the FCR series, indicating a robust COD removal capacity at this HRT. During the 16-hour HRT operation, the average influent and effluent COD concentrations were $641.6 \text{ mg/L} \pm 130.25 \text{ mg/L}$ and $78.4 \text{ mg/L} \pm 14.83 \text{ mg/L}$, respectively, with an SALR of approximately $7.9 \text{ g/m}^2/\text{day}$. Similar to the 12-hour HRT, the final effluent complied with PermenLH No. 3/2010. However, in contrast to the 12-hour HRT, where the standard was achieved at R5, compliance with the national standard was only achieved at R6 under the 16-hour HRT condition. For the 24-hour HRT operation, the average influent and effluent COD concentrations were $654.2 \text{ mg/L} \pm 79.5 \text{ mg/L}$ and $90.2 \text{ mg/L} \pm 8.2 \text{ mg/L}$, respectively, with an SALR of approximately $5.6 \text{ g/m}^2/\text{day}$. Similar to the 16-hour HRT, the COD concentration met the national standard at R6, indicating a similar treatment performance trend at longer HRTs.

Comparing HRT performance should also consider the SALR, as this parameter is directly influenced by HRT duration and influent discharge into the reactor. Among the three HRT variations, the 12-hour HRT produced the lowest COD effluent concentration despite having the highest SALR, demonstrating its superior COD removal efficiency. Interestingly, the SALR at WWTP Jababeka is approximately $6.11 \text{ g/m}^2/\text{day}$, meaning that the SALR in the 12-hour HRT experiment was about 1.75 times higher yet still achieved the best COD removal efficiency. This suggests that the FCR system can maintain high performance even under higher organic loading conditions, highlighting its robustness in industrial estate wastewater treatment.

The highest COD removal efficiency was achieved at HRT 12 hours, with an average removal rate of $90.79\% \pm 1.59\%$, demonstrating the strong performance of the FCR system in industrial estate wastewater treatment. Compared to other studies utilizing similar IFAS-based technologies, such as the multilevel contact oxidation process (MLCOP), the COD removal efficiency in this study is notably high. MLCOP, which does not integrate constructed wetlands (CW), has been reported to achieve 86.86% COD removal in poultry wastewater treatment (Zheng et al., 2019) and 83.8% in automobile painting wastewater treatment (P. Li et al., 2015). Another study found that when combined with coagulation-hydrolysis-acidification, MLCOP could remove 80–98% of COD from dye wastewater (Zhu et al., 2017). The high COD removal efficiency observed in this study suggests that the integration of IFAS with CW in the FCR system enhances organic pollutant degradation compared to IFAS alone. This highlights the potential of FCR technology as a highly effective and sustainable alternative for industrial estate wastewater treatment.

An analysis of COD reduction trends across each reactor stage reveals a consistent decrease in COD concentrations across all three HRT variations (see Figure 3). The most significant COD reduction occurs in Reactor R1, where COD levels drop by 36%–41% from the influent, highlighting the crucial role of the initial treatment stage. This can be attributed to the high availability of organic carbon in the influent, which serves as a rich substrate for microbial activity, leading to rapid COD degradation (Ahmed et al., 2022; Akula et al., 2021). Additionally, the abundant organic matter in the first reactor fosters a robust microbial community, further enhancing organic pollutant breakdown (Wang et al., 2024).

Conversely, the lowest COD reduction is observed between R5 and R6, particularly in the final reactor stage. As wastewater progresses through the treatment series, organic load decreases, leading to limited substrate availability for microbial degradation in the later reactors. At this stage, the system likely shifts from primary COD removal to effluent polishing, targeting the removal of residual nutrients and fine particulate matter to meet discharge standards rather than achieving substantial COD reduction (Kavousi & Borghei, 2023). This trend underscores the differentiated functional roles of each reactor stage, with early reactors prioritizing bulk COD removal and later reactors focusing on effluent refinement to ensure compliance with environmental regulations.

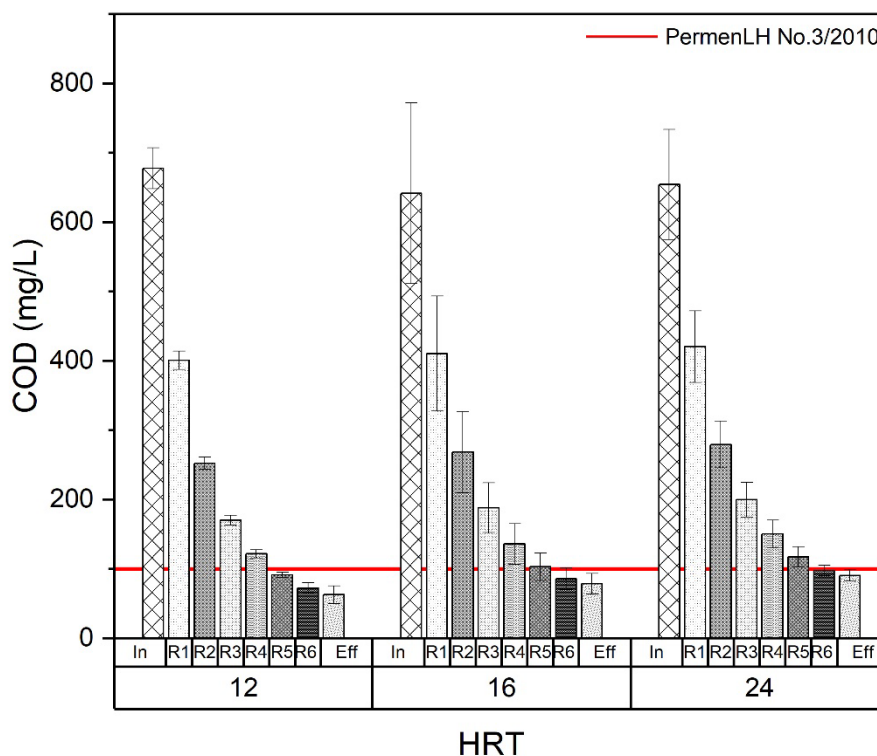


Figure 3. COD removal profile across reactor stages at different HRT variations (12, 16, and 24 hours) in the FCR system

Ammonia-Nitrogen Removal

Figure 4 illustrates the ammonia-nitrogen removal profile across the reactor series for all three HRT variations. In all cases, the ammonia nitrogen in the final effluent successfully met the national discharge standard for industrial estate wastewater treatment plants (PermenLH No. 3/2010). The removal trend within the reactor stages shows that R1 consistently exhibited the highest ammonia-nitrogen reduction across all HRT cycles, with removal efficiencies ranging between 34% and 69%. Similar to the COD removal trend, the first reactor receives the highest nutrient load, allowing for more efficient processing by the microbial community. As wastewater progresses through the reactor series, nutrient availability decreases, which may lead to reduced microbial activity and lower ammonia removal efficiency in later reactors (Buzoianu et al., 2016). The higher initial COD concentration in the influent may contribute to greater microbial activity in R1, potentially leading to enhanced biofilm development and ammonia removal efficiency, as biofilms provide a surface for ammonia-oxidizing bacteria (AOB) to thrive (Fatimah & Donnelly, 2009).

Figure 4 further suggests that ammonia-nitrogen removal trends fluctuate beyond R1 across different HRT variations. These fluctuations may be attributed to shifting microbial dynamics, particularly the interaction between AOB and nitrite-oxidizing bacteria (NOB), as well as competition with heterotrophic bacteria (Fatimah & Donnelly, 2009). The balance between these microbial groups is highly dynamic and can be influenced by the residual COD concentration in each reactor stage. When COD levels remain high, heterotrophic bacteria may outcompete AOB for available oxygen and space, leading to lower ammonia oxidation efficiency. Conversely, in reactors where COD concentrations decline, conditions may become more favorable for AOB proliferation, enhancing ammonia removal efficiency (Zhang et al., 2015). Furthermore,

higher COD reduction in the initial reactors may also contribute to increased ammonia-nitrogen assimilation for biomass formation, suggesting that ammonia removal in R1 could be influenced by both AOB activity and heterotrophic bacterial assimilation (Bonassa et al., 2021; Sui et al., 2024).

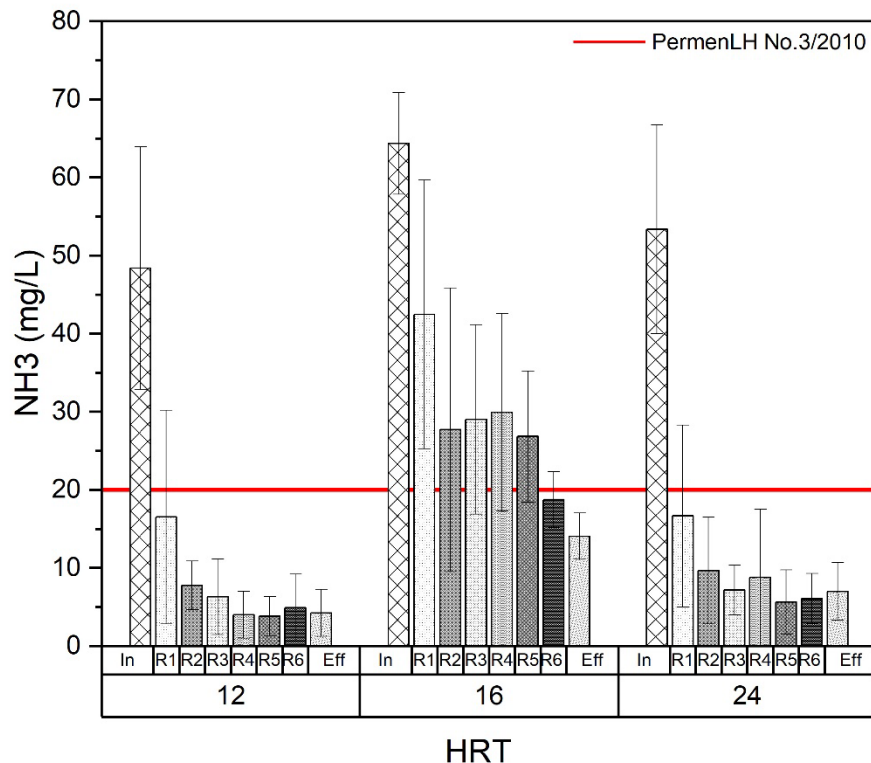


Figure 4. Ammonia-nitrogen removal profile across reactor stages at different HRT variations (12, 16, and 24 hours) in the FCR system

Phosphate Removal

Figure 5 illustrates phosphate removal from industrial estate wastewater across each FCR reactor stage for all HRT variations. In all cases, the final effluent successfully met the national discharge standard for industrial estate wastewater treatment plants (PP No.2/2021 Class III limit standard). However, unlike COD and ammonia removal, phosphate removal did not exhibit a clear downward trend from R1 to R6 in any of the HRT variations. Instead, an increase in phosphate concentration was observed in certain reactors compared to the preceding stage. This suggests that phosphorus removal is influenced by complex mechanisms, including secondary phosphorus release, which can occur under anoxic or anaerobic conditions within the reactor (Deng et al., 2016).

Given that FCR is an attached-growth reactor, it is possible that biofilm formation on the attached media contributes to localized anaerobic or anoxic conditions within the microstructure of the bacterial growth matrix. Oxygen penetration becomes limited when biofilm thickness exceeds 600 μm , potentially creating conditions that facilitate phosphorus release rather than removal (Yu et al., 2004). Additionally, the microbial community responsible for phosphorus removal is more diverse and sensitive to operational conditions compared to those involved in COD and ammonia removal. The presence of nitrate, for instance, can introduce competition for carbon sources between

phosphorus-accumulating organisms (PAOs) and denitrifying bacteria, potentially complicating the phosphorus removal process (Zou et al., 2006). This competition may lead to reduced phosphorus removal efficiency when both nitrate and acetate are present.

Although nitrite and nitrate concentrations were not directly measured in this study, the observed ammonia removal trend suggests that nitrification may have occurred, resulting in the formation of nitrite and nitrate. These compounds could have influenced phosphate dynamics within the reactor, potentially affecting overall phosphorus removal performance. However, further investigation would be required to determine the specific interactions between nitrification byproducts and phosphorus removal mechanisms in the system.

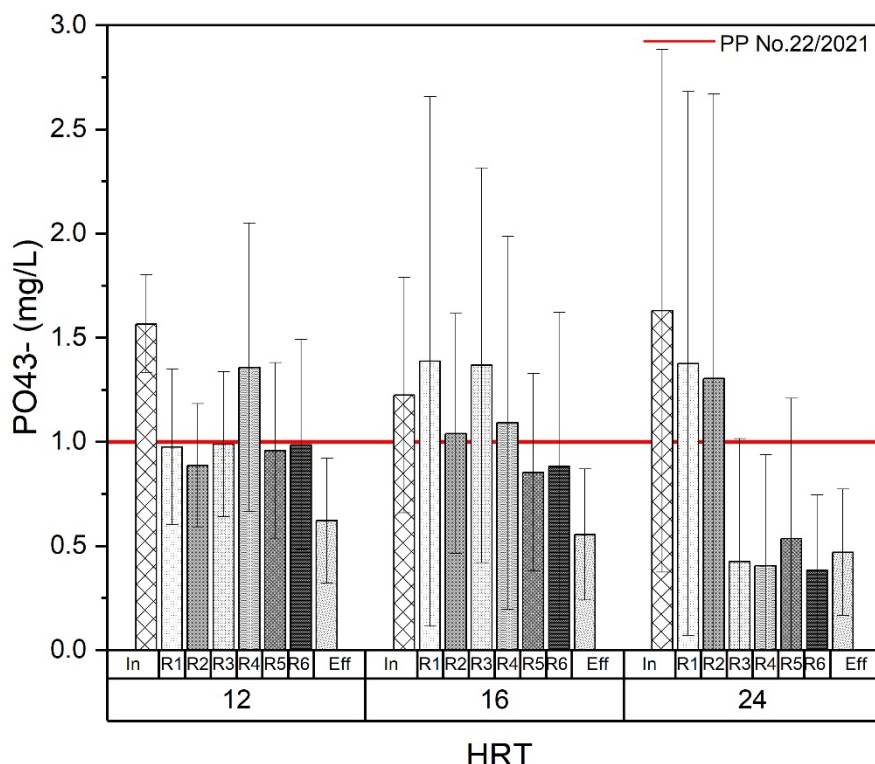


Figure 5. Phosphate removal profile across reactor stages at different HRT variations (12, 16, and 24 hours) in the FCR system

Nickel Removal

Figure 6 illustrates nickel removal from industrial estate wastewater using the FCR reactor across each treatment stage and for all HRT variations. Notably, the nickel concentration from influent to effluent remained below the regulatory discharge limit set by PermenLH No. 3/2010. The purpose of analyzing nickel in this study was to assess the potential of the FCR system in reducing heavy metal concentrations in industrial wastewater. A decreasing trend in nickel concentration was observed from R1 to the final reactor stage across all HRT variations, indicating progressive removal throughout the system. The highest nickel reduction occurred in R1 for each HRT variation, with removal efficiencies ranging between 20% and 47%.

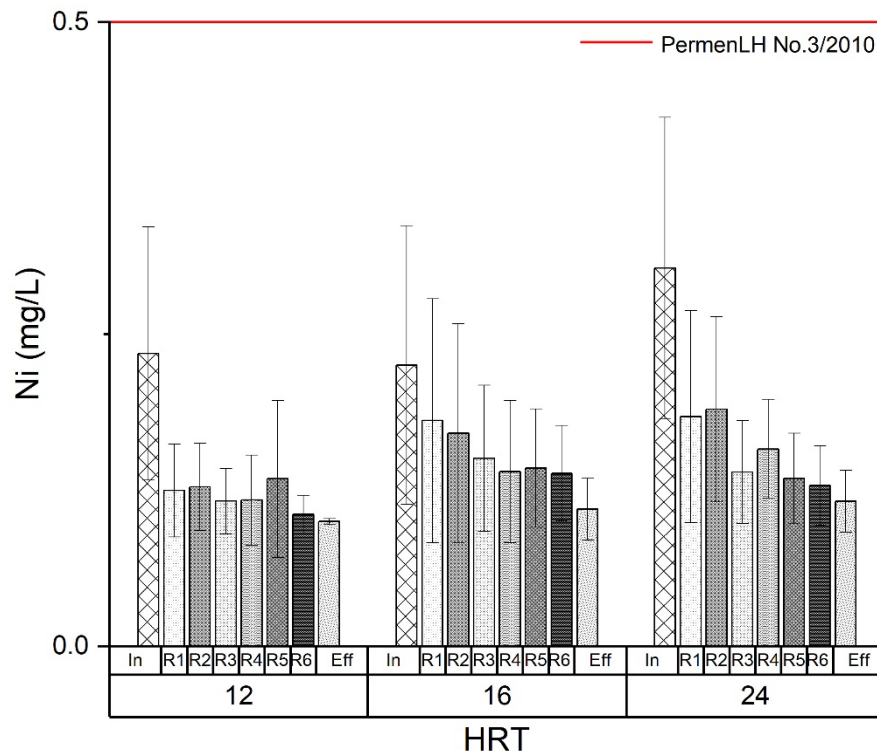


Figure 6. Nickel removal profile across reactor stages at different HRT variations (12, 16, and 24 hours) in the FCR system

When compared to constructed wetlands (CWs) designed as a series of reactors, the first reactor typically encounters the highest metal concentrations, resulting in greater removal efficiency. This may be due to the higher availability of metals for adsorption and uptake by plant roots and reactive substrates in the early treatment stages (Knox et al., 2010; Kumar et al., 2020). Additionally, the hydraulic loading rate (HLR) appears to play a role in removal efficiency, as higher HLRs in the first reactor increase contact time between wastewater and reactive surfaces, potentially enhancing metal adsorption and precipitation (Sun et al., 2019). The redox conditions in R1 may also favor the precipitation and co-precipitation of metals, while changing redox dynamics in later reactors could influence metal removal efficiency (Mozaffari et al., 2021).

It is important to note that metal reduction in the FCR reactor is not solely attributed to plant uptake but may also be influenced by biosorption from microbial biofilms attached to the reactor media (Kosolapov et al., 2004). These findings suggest that FCR technology has the potential to contribute to heavy metal removal in industrial wastewater treatment. However, further investigation is needed to fully understand the interactions between microbial biosorption, plant uptake, and adsorption mechanisms within the system. While this study provides insights into nickel removal trends in the FCR reactor, additional research on metal binding mechanisms and long-term performance under varying wastewater compositions would be beneficial for optimizing treatment efficiency.

Effect of HRT to COD, NH₃-N, PO₄³⁻, and Nickel Removal

Table 1 presents the FCR performance analysis results comparing pollutant removal efficiencies at different HRTs. The statistical analysis shows that COD, NH₃-N, PO₄³⁻, and nickel removal efficiencies range from 86% to 90.79%, 77.92% to 88.96%, 54.76%

to 63.09%, and 40.85% to 51.99%, respectively. When ranked in terms of removal efficiency, the order from highest to lowest is $\text{COD} > \text{NH}_3\text{-N} > \text{PO}_4^{3-} > \text{Ni}$, indicating that the FCR system is particularly effective in removing COD and ammonia compared to phosphorus and nickel.

Table 1. Pollutant removal efficiency at different hydraulic retention times (HRTs)

HRT	Removal Efficiency (%)			
	COD	$\text{NH}_3\text{-N}$	PO_4^{3-}	Ni
12 hr	90.79% $\pm$ 1.59%	88.96% $\pm$ 10.51%	61.67% $\pm$ 17.21%	49.82% $\pm$ 23.44%
16 hr	87.75% $\pm$ 0.29%	77.92% $\pm$ 5.29%	54.76% $\pm$ 11.88%	40.83% $\pm$ 28.90%
24 hr	86.16% $\pm$ 0.65%	86.90% $\pm$ 7.41%	63.09% $\pm$ 20.68%	51.99% $\pm$ 30.79%
P-value	<0.0001	0.1097	0.7167	0.8017

In terms of nutrient removal, the lower phosphate removal efficiency compared to ammonia removal can be attributed to the competition between polyphosphate-accumulating organisms (PAOs) and denitrifying bacteria for available COD. Since both phosphorus removal and denitrification rely heavily on COD availability, a COD-limited system may favor denitrifiers over PAOs, reducing phosphate removal efficiency (Hamada et al., 2006; Vaboliene & Matuzevičius, 2005). This also explains why a higher SALR resulted in greater COD and ammonia removal, as a higher organic load supports a more active microbial community that requires sufficient carbon sources for metabolism. The trend observed in this study is consistent with previous findings in IFAS-based systems, where COD and nitrogen removal tend to outperform phosphorus removal due to similar COD competition dynamics (Lan et al., 2024; Wang et al., 2018).

For nickel removal, the lower efficiency observed is likely due to the already low initial concentration, which was within the national standard limit (0.5 mg/L). In biological wastewater treatment, nickel removal primarily occurs through biosorption and bioaccumulation (Azimi et al., 2009). However, these processes tend to be less effective for nickel compared to other metals due to its specific chemical interactions with biological materials. Studies have shown that biosorbents generally exhibit lower adsorption capacities for nickel than for other heavy metals, which may explain its lower removal efficiency in this study (Hawari & Mulligan, 2006).

The statistical significance of HRT's effect on pollutant removal was further assessed using one-way ANOVA. Table 1 shows that among all pollutants, only COD removal exhibited a highly significant response to HRT ($p < 0.0001$), while $\text{NH}_3\text{-N}$, PO_4^{3-} , and nickel removal efficiencies showed no significant variation with HRT ($p > 0.05$). This indicates that HRT has a strong influence on COD removal but does not significantly impact the removal of ammonia, phosphate, or nickel. The observed results align with previous studies where organic matter degradation in wastewater treatment process is more sensitive to retention time changes than nutrient or heavy metal removal (Luo et al., 2024; Xu et al., 2014).

To further explore the relationship between HRT and pollutant removal efficiency, Tukey's HSD post-hoc test was conducted, and Figure 7 presents the correlation analysis results. The correlation between HRT and COD removal efficiency ($r = -0.84$) suggests a strong negative relationship, indicating that shorter HRTs result in higher COD removal efficiency. This finding is consistent with previous research on IFAS and biofilm-based treatment systems, which also reported higher COD removal rates at shorter HRTs due to enhanced microbial activity and substrate availability (Maulidiany, 2022). However, HRT showed minimal correlation with $\text{NH}_3\text{-N}$ ($r = 0.0078$), phosphate ($r = 0.08$), and

nickel ($r = 0.07$) removal efficiencies, suggesting that retention time does not significantly influence these removal processes. This further implies that other factors, such as adsorption, or chemical precipitation, may play a more dominant role in the removal of nutrients and heavy metals (Gadd, 2009; Pedemonte et al., 2016; Rosca et al., 2016).

The relationships between different pollutant removal efficiencies also indicate low correlation values, suggesting largely independent removal mechanisms. The correlation between COD removal and $\text{NH}_3\text{-N}$ removal ($r = 0.051$), phosphate removal ($r = -0.015$), and nickel removal ($r = -0.067$) is weak, indicating that organic matter degradation does not strongly impact nutrient or metal removal in the system. Similarly, $\text{NH}_3\text{-N}$ removal is weakly correlated with phosphate removal ($r = -0.07$) and nickel removal ($r = 0.062$), further suggesting that nitrification operates independently of phosphate and metal removal processes. The only slightly higher correlation observed is between phosphate and nickel removal ($r = 0.23$), which may indicate some common removal mechanisms, such as adsorption onto reactor media or co-precipitation, though the relationship remains weak.

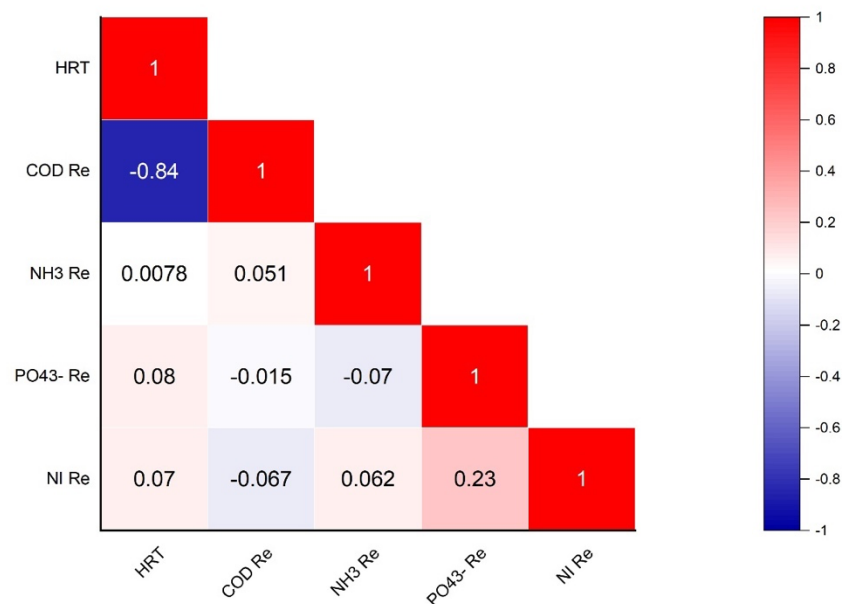


Figure 7. Correlation between hydraulic retention time (HRT) and pollutant removal efficiencies

These findings suggest that while HRT significantly impacts COD removal, its effect on other pollutants is negligible, indicating that phosphorus and metal removal mechanisms are influenced by different operational or environmental factors. The weak correlations among most pollutant removal efficiencies highlight that each parameter likely follows a distinct removal pathway, rather than being interconnected through microbial or chemical interactions. Given these results, further investigation into microbial activity, adsorption dynamics, and reactor conditions is necessary to better understand and optimize the pollutant removal processes in the FCR system. Future research should also explore alternative design modifications, such as enhanced biofilm carriers or improved aeration strategies, to maximize phosphorus and metal removal efficiency in attached-growth reactors.

Conclusion

This study evaluated the optimal hydraulic retention time (HRT) for FCR technology in removing COD, nitrogen, phosphorus, and nickel from industrial estate wastewater. The results indicate that HRT significantly affects COD removal, with the 12-hour HRT achieving the highest efficiency ($90.79\% \pm 1.59\%$), while its impact on ammonia, phosphate, and nickel removal was minimal. Statistical analysis using ANOVA confirmed that HRT had a highly significant effect ($p < 0.0001$) on COD removal, whereas ammonia, phosphate, and nickel removal efficiencies were not significantly influenced by retention time ($p > 0.05$). The weak correlations among pollutant removal efficiencies further suggest that each parameter follows distinct removal mechanisms rather than being interconnected through microbial or chemical pathways.

These findings highlight the potential of FCR technology as an efficient and sustainable alternative for industrial estate wastewater treatment, particularly for organic pollutant removal. However, nutrient and heavy metal removal may appear to be governed by other factors, such as microbial interactions, redox conditions, and adsorption dynamics, rather than HRT alone. Further research is needed to optimize phosphorus and metal removal in FCR systems, potentially through enhanced biofilm carriers, improved aeration strategies, or modified organic loading conditions.

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