Feasibility Study of Moving Bed Biofilm Reactor (MBBR) Technology at Guheshwori Wastewater Treatment Plant, Nepal

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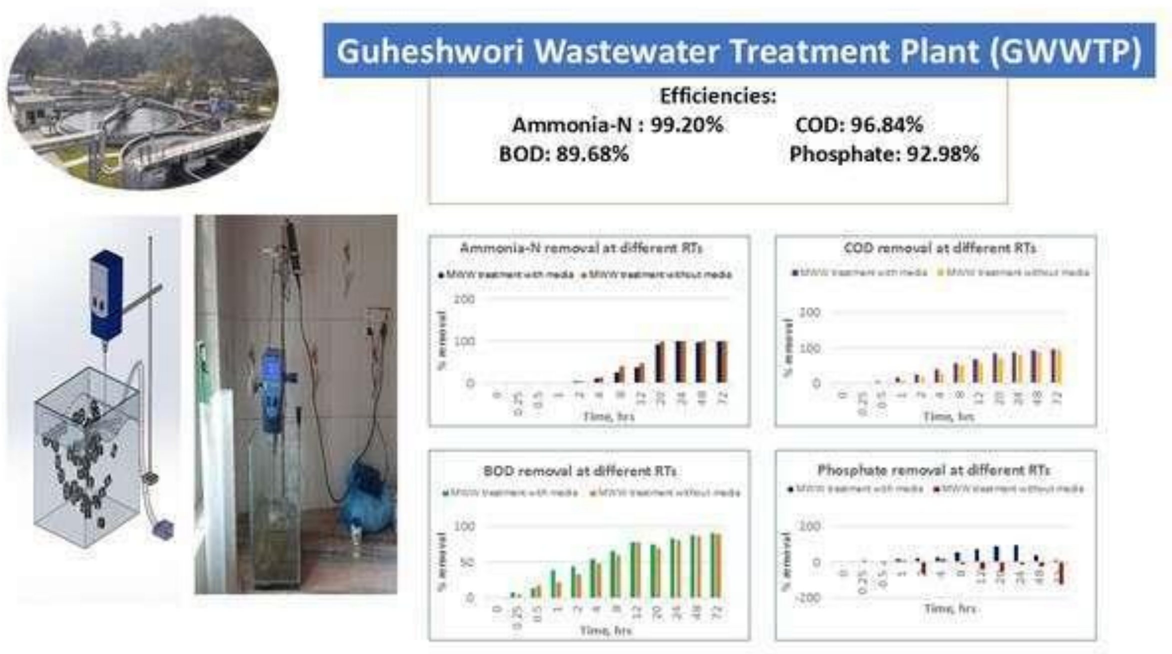
Graphical Abstract:



ABSTRACT

Moving Bed Biofilm Reactor (MBBR) technology is applicable for removing organic components and nitrogen from wastewater in the Guheshwori Wastewater Treatment Plant (GWWTP). A lab-scale single-staged aerobic batch MBBR (16L pure volume, 5L active working volume) was designed and initiated using synthetic and municipal wastewater in two phases. Removal efficiencies of COD,

BOD, NH_4-N, and PO_4^{3-} were investigated at various retention times (0-72h) for municipal wastewater treatment with and without media. Physical parameters (pH, DO, temperature, and conductivity) were monitored under ambient conditions. Both treatments demonstrated similar BOD removals (89.68% and 88.97%) at 72h, with the treatment using media exhibiting higher COD removal (96.84%). Ammonia-nitrogen removal was completed at 20h for the treatment without media and 99.20% at 24h for the treatment with media. Phosphate removal was significant (92.98%) at 24h for MBBR with media, whereas no notable phosphate removal was observed without media. MBBR is efficient in BOD, COD, ammonia-nitrogen, and phosphate removal from municipal wastewater, offering advantages over traditional activated sludge processes regarding tank size. The findings support the feasibility of implementing MBBR for wastewater treatment at GWWTP.
Keywords: Removal efficiencies, Municipal wastewater treatment, Synthetic wastewater, Activated Sludge Process, Media

1. Introduction

Wastewater has emerged as a global concern due to rapidly growing populations, swift economic expansion, industrialization, and varying technical and institutional capabilities (UNESCO, 2017). The world produces billions of liters of sewage daily, and its management depends on local handling practices (Mateo-Sagasta et al., 2015). A country's income affects the degree of wastewater treatment; high-income countries treat approximately 70% of municipal and industrial wastewater, while low-income countries only manage an average of around 8% (Mateo-Sagasta et al., 2015).

Nepal, categorized as one of the least developed nations with a low income and Human Development Index (HDI) of 0.602 (UNDP Nepal, 2022), serves as an illustrative case with only 12% of its wastewater receiving treatment (Ramtel et al., 2021). In 2013, UNESCO reported Nepal as having the lowest wastewater treatment levels in the Asia-Pacific Region, despite being the fifth-fastest urbanizing country from 1990 to 2018 (UN, 2018).

In the Kathmandu Valley, there are currently five municipal wastewater treatment plants: an activated sludge facility at Guheshwori, non-aerated lagoons at Kodku and Dhobighat, and aerated lagoons at Sallaghari and Hanumanghat, with many other small, decentralized wastewater treatment systems (DEWATS) installed around the valley (Ramtel et al., 2021). The activated sludge system at the Guheshwori Wastewater Treatment Plant (GWWTP) is the sole operational plant as of January 2002 which has 17.3 million liters per day of wastewater (Shrestha et al., 2015). The fate of the collected wastewater is less than ideal, leading to the direct discharge of effluent into the Bagmati River system (Regmi, 2013). The plant employs a combination of aerobic and anaerobic methods to facilitate the natural bacterial decomposition of sewage before its integration into the river. A study by (Thapa et al., 2019) contended that nutrient removal efficiency at GWWTP remained notably deficient. The yield was alarmingly low, implying that the existing biological processes inadequately assisted the WWTP in pollutant removal. Despite that, plants face soaring energy expenditures, limited space availability, and high maintenance expenses (Timilsina, 2010).

The use of innovative and effective technologies helps to overcome these challenges (Biswas et al., 2014). Both physical and biological treatment methodologies are meant to treat wastewater for environmental certification. The cost of chemicals, equipment, excess sludge handling, and disposal makes physicochemical techniques costlier than biological approaches. Biological treatment rests upon microorganisms that can biodegrade organic matter, rendering them the favored choice for wastewater treatment (Porsgaard & Soderstrom, 2015).

Biological processes circumvent certain challenges associated with the activated sludge method used in GWWTP, such as the need for extensive reactor dimensions, settling tanks, and the recycling process. A Moving Bed Biofilm Reactor (MBBR) system is an entirely mixed and perpetually operational biofilm reactor, where biomass flourishes on diminutive carrier elements exhibiting slightly lower density than water. These carriers are kept in constant motion within the reactor, accompanied by a stream of water. Former biological treatment methodologies, like trickling filters and granular media biofilters, suffered from space-intensive requirements or the need for recurrent backwashing (Porsgaard & Soderstrom, 2015). The MBBR technology was meticulously engineered to counter these drawbacks and has subsequently gained prominence across various treatment facilities, offering operational economy and obviating the need for sludge recycling (Renou et al., 2008).

The MBBR system showcases heightened efficiency in eliminating chemical oxygen demand, ammonia-nitrogen concentration, and organic loading. It also demands reduced Hydraulic Retention Time (HRT) to achieve optimal levels of organic load reduction, thereby resulting in a diminished aeration tank volume (Cao & Zhao, 2012; Javid et al., 2013). This means less sludge production than that of conventional methods, which ultimately reduce disposal costs for the sludge, making the plant efficient economically. The principal objective of this investigation revolves around assessing the viability of integrating MBBR technology within the GWWTP framework. The specific aims encompass delineating the distinctive attributes of wastewater at GWWTP and scrutinizing alterations in physicochemical parameters following treatment. The outcomes of this feasibility inquiry could hold significant utility in appreciating the indispensability of MBBR and integrating this advancement into forthcoming wastewater treatment plants within Nepal's purview. Nevertheless, the study's potential limitation lies in its inability to achieve long-term MBBR performance under continuous operational conditions during the study's duration. In addition, the study does not incorporate the socio-economic criteria of the feasibility aspect.

2. Methods and Methodology

2.1. Study Area

Guheshwori Wastewater Treatment Plant (GWWTP) was designated as the study site which is positioned in the northeastern segment of Kathmandu Metropolitan City, specifically in ward no. 8, in proximity to the banks of the Bagmati River. Situated at an altitude of 4600 feet, the GWWTP's coordinates are situated at a latitude of 27° 42’ 45.3” N and a longitude of 85° 21’ 25.6” E (Figure 1). The existing GWWTP occupies an area spanning 5.0 hectares (KUKL, 2013).

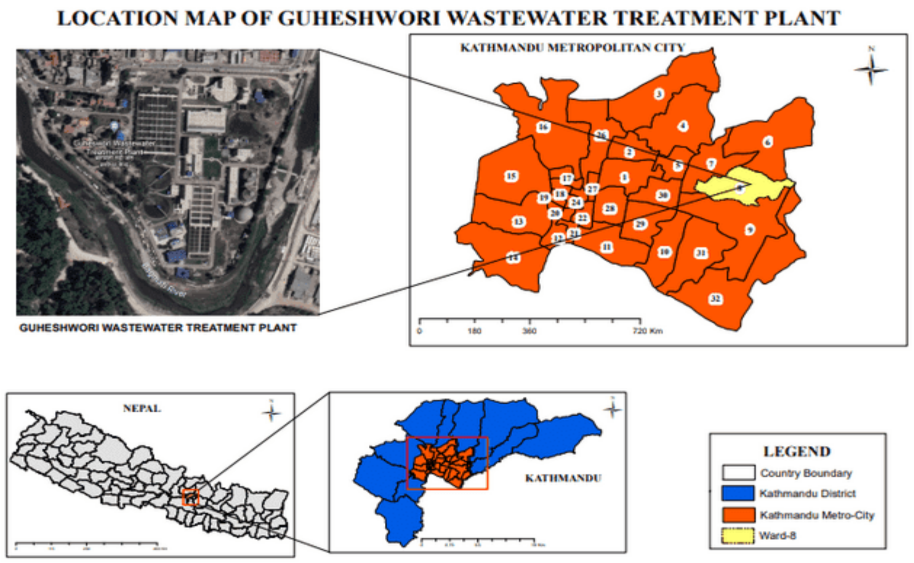


Figure 1. Location map of GWWTP

2.2. Sampling

Total of 40 liters of wastewater samples were collected for the research purpose, drawn from the inlet of the Guheshwori Wastewater Treatment Plant (GWWTP). These samples were collected in two separate gallons, each holding 10 liters. The sampling was carried out on three occasions: at the close of July and in the middle of August and September. During the sampling process, parameters such as pH, dissolved oxygen, temperature, and conductivity were gaged directly on-site. The wastewater samples were subsequently transported to the Soil, Water and Air Testing Laboratories and stored at a temperature of 4°C. Likewise, the lab-scale MBBR yielded daily samples that were also preserved at 4°C for further analysis. The analyzes of all the samples were executed in accordance with established standard methodologies employed for the examination of water and wastewater.

2.3. Experimental Design and Setup

Figure 2. Experimental set-up of MBBR: A. 3D diagram of the reactor B. Actual set-up of the reactor

The designed MBBR is a single-staged aerobic batch reactor manufactured from 3mm-thick glass, as shown in Figure 2. The reactor's total capacity measured approximately 16 liters, while the functional working capacity amounted to 5 liters (for both synthetic and domestic wastewater). The reactor configuration encompasses an SP-780 aerator, featuring dual air outlets delivering 3.5 L/min, a crucial component to uphold optimal dissolved oxygen levels conducive to microbial proliferation. To facilitate effective media blending within the reactor, a PFC BIOMAX media (Table 1) was incorporated, presenting an expansive surface area of 900 m^2/m^3 with 40% filling ratio. The media has a porous circular structure with concentric circles with internal radials and extended external fins to provide high surface area for microbial growth. Further enhancing operational dynamics, a continuous mechanical stirrer of model SH-II-6C was engaged, operating within a rotational speed range of 100 to 200 rpm, ensuring consistent and thorough mixing of the media throughout the reactor.

Table 1. Media specifications of PFC BIOMAX media

Surface Area	900 m^2/m^3
Material of Composition (MOC)	19 mm diameter*10 mm height
Specific gravity	0.94-0.95 gm/cm^3
Voidage	> 98.5%
Colour	Virgin clear transparent

2.4. MBBR operating conditions

2.4.1. Synthetic wastewater preparation

The recipe prescribed by (Yang et al., 2018) served as the blueprint for formulating the synthetic wastewater that imitates municipal sewage. This synthetic wastewater (SWW) predominantly featured glucose as its primary substrate. The constituents of the synthetic wastewater were as follows: glucose at a concentration of 1000 mg/L; NH_4Cl ranging from 125 to 191 mg/L; K_2HPO_4 at 44 mg/L; and a trace element solution at a ratio of 1 mL per liter of solution. The trace element solution, in turn, consisted 1.5 mg/L of $CaCl_2$, 10 mg/L of EDTA, 1.1 mg/L of $CuCl_2 \cdot 2H_2O$, 0.003 mg/L of H_3BO_3, 0.003 mg/L of Na_2SeO_3, 1.2 mg/L of $MgSO_4 \cdot 7H_2O$, 0.28 mg/L of $FeSO_4 \cdot 7H_2O$, 0.2 mg/L of $ZnSO_4 \cdot 7H_2O$, 0.11 mg/L of $MnSO_4 \cdot H_2O$, and 0.06 mg/L of $CoSO_4 \cdot 7H_2O$. Additionally, $NaHCO_3$ was introduced into the influent, with a concentration of 100 mg/L, to sustain the pH of the MBBRs suspension within the range of 6.5 to 7.5.

2.4.2. Initiation of the reactor under optimal condition

To foster optimal microbial proliferation within the slurry environment, the bioreactor was initiated in a dual-phase approach, utilizing both laboratory-prepared SWW and actual municipal wastewater sourced from the GWWTP. For each cycle, the reactor was inoculated with approximately 5 mL of activated sludge procured from the GWWTP which was pivotal to ensuring robust biological growth and the enhancement of biofilm before introducing new feed for both synthetic and municipal wastewater. Biofilm, according to the definition is complex heterogenous micro-ecosystem of microbial community interactions that share the same environment (Flemming et al., 2016). Adsorption of macromolecules and nutrient to the surface, early cell movement, adhesion, and irreversible attachment are all steps of biofilm development (Zhu et al., 2015). Intermittent air was introduced into the reactor through an aeration system connected to two pipes located at the reactor's base to stabilize the Mixed Liquor Suspended Solids (MLSS) of the wastewater and maintain Dissolved Oxygen (DO) levels above 2 mg/L. Similarly, a mechanical stirrer was employed to ensure thorough mixing of the carrier media, a vital aspect in enhancing the successful development of the biofilm.

During the initial phase, the reactor was primed with synthetic wastewater (SWW) and operated for a span of 10 days. Operating in batch mode, fresh SWW was introduced at 48-hour intervals for this 10-day adaptation period. Before each new feed cycle, the sludge was allowed to settle, retaining it within the reactor, while the remaining effluent was discharged. Consequently, the reactor was replenished with freshly prepared synthetic sewage.

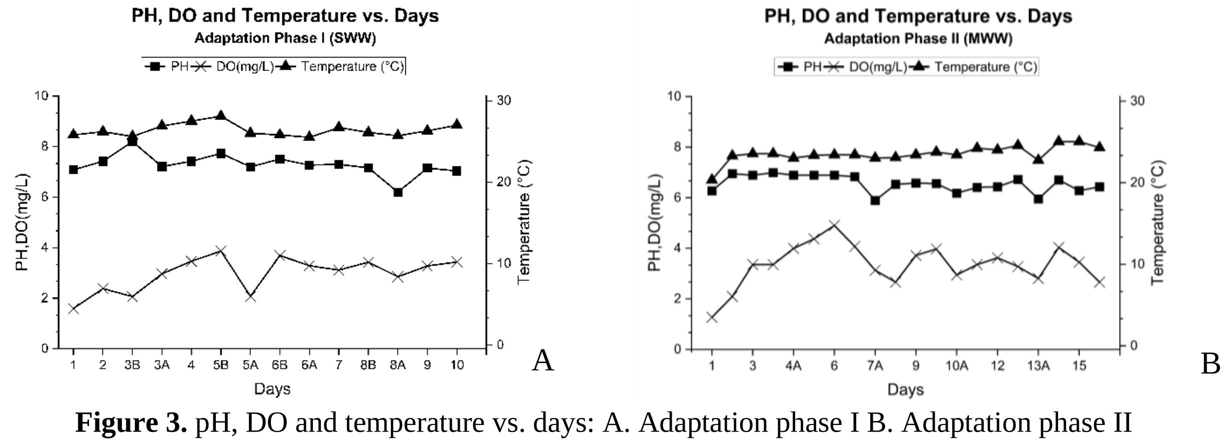


Figure 3. pH, DO and temperature vs. days: A. Adaptation phase I B. Adaptation phase II

Following the 10-day adaptation period in SWW, the second phase commenced, involving the introduction of municipal wastewater (MWW) from the GWWTP into the reactor for the adaptation of both sludge and microorganisms. This phase of adaptation within municipal wastewater (MWW) extended for approximately 15 days. During this interval, new feeds were supplied every 72 hours, with each feed introducing 5-10 mL of activated sludge. Before each new feed cycle, approximately 1 to 2.5 liters of MWW was replaced within the reactor.

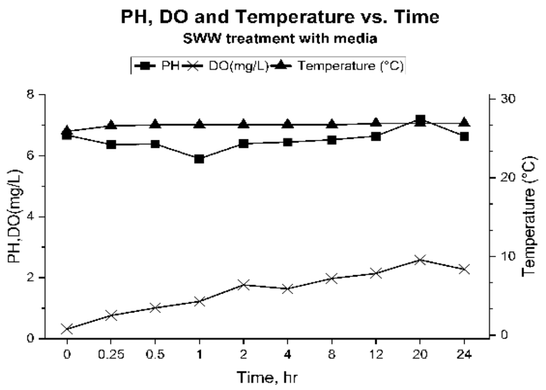
Throughout both adaptation phases, the DO concentration was consistently maintained above 2 mg/L. The pH, which fluctuated between 6.2 and 8.2, remained unadjusted, devoid of any Hydrochloric Acid (HCl) or Sodium Hydroxide (NaOH) additions. During the acclimation of sludge and microorganisms in SWW and MWW, the laboratory maintained a temperature range of 20.7 to 28.1°C. The entire study was conducted under ambient conditions. Daily samples were systematically acquired from the bioreactor, enabling the analysis of fluctuations in physicochemical parameters throughout the adaptation phases I and II. Key physical parameters, including pH, DO concentration, temperature, and conductivity, were vigilantly monitored over the course of the study.

It has worth noting that by the culmination of the adaptation period, initial biofilm layers had become apparent on the inner surfaces of the K3 carriers. Also, the external surfaces of the carriers exhibited a slippery texture.

2.4.3. Treatment at different Retention Times

Upon the successful acclimatization of biomass and microorganisms to both synthetic and municipal wastewater, the investigation shifted to assessing the efficacy of removing chemical parameters such as Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Ammonia-Nitrogen (NH_4-N), and Phosphate (PO_4^{3-}) under various Retention Times (RTs): 0h, 0.25h, 0.5h, 1h, 2h, 4h, 8h, 12h, 20h, 24h, 48h, and 72h. Diverse treatment scenarios were enacted, involving the injection of SWW with media and MWW with and without media.

Physical parameters such as pH, DO concentration, temperature and conductivity were monitored at different RTs over the period of study (Figure 4). During the treatment of SWW with media, pH, temperature, and DO were between the range of 5.9 and 7.2, 25.9 and 26.9°C & 0.4 and 3.3 mg/L respectively. Similarly, for the treatment of MWW with media, pH, temperature, and DO were between the range 6 and 7.5, 23.5 and 24.2°C & 1.5 and 3.3 mg/L respectively. Likewise, for the treatment of MWW without media, pH, temperature, and DO were between the range 6.6 and 7.5, 23.4 and 24.2°C & 1.4 and 3.8 mg/L respectively.



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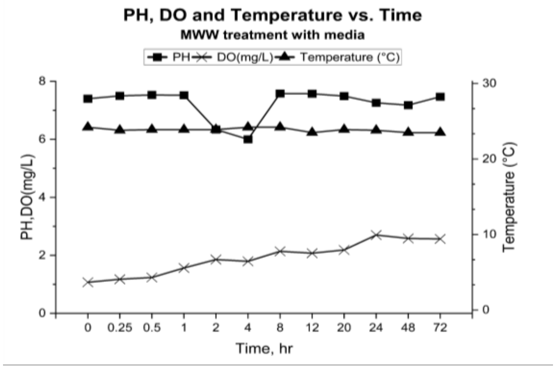

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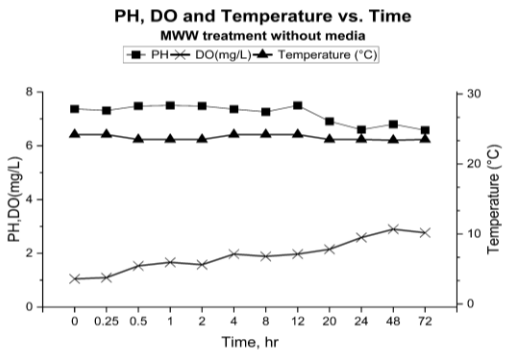

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Figure 4. pH, DO and temperature vs. days: A. SWW treatment with media B. MWW treatment with media C. MWW treatment without media

2.5. Analytical methods

All assessments of the parameters adhered to established standardized methods (APHA) and are succinctly presented in Table 2.

Table 2. Analytical methods used for physicochemical characterization of wastewater samples

S.N.	**Parameters, unit**	**Methodology/ INSTRUMENTS**
1.	PH	PH METER (MILWAUKEE INSTRUMENTS, PH55 PRO, EUROPE)
2.	Turbidity, NTU	Turbidity meter (Lovibond, TB 210 IR, Germany)
3.	DO, MG/L	DO PROBE (OXY 7 VIO-XS, ITALY)
4.	Conductivity, mS/cm	Conductivity meter (COND7 Vio Set, 2301T, Italy)
5.	TOTAL SOLIDS (TS), MG/L	2540 B., APHA 23RD EDITION

6.	Total Suspended Solids (TSS), mg/L	Gravimetric Method, 2540 D., APHA 23rd edition
7.	TOTAL DISSOLVED SOLIDS (TDS), MG/L	GRAVIMETRIC METHOD, 2540 C., APHA 23RD EDITION
8.	COD, mg/L	Closed Reflux, Colorimetric Method, 5220 D., APHA 23rd edition
9.	BOD5, MG/L	5-DAY BOD, 5210 B., APHA 23RD EDITION
10.	Ammonia-Nitrogen, mg/L	Phenate method, 4500 NH3 F., APHA 23rd edition

3. Results and Discussion

3.1. Physico-chemical characteristics of wastewater

The constitution of municipal or domestic wastewater exhibits seasonal fluctuations, giving rise to corresponding impacts on flow patterns, physicochemical attributes, and constituent concentrations at the inlet of wastewater treatment facilities. As part of this dynamic, a wastewater sample was procured from the GWWTP during the zenith of the monsoon season. This sample was subsequently subjected to laboratory analysis, with the intent of gaging its inherent pollution potential before undergoing treatment within MBBR.

To provide a broader context for our findings, we compared our results with data from previous studies conducted by (Thapa et al., 2019) and (S. Shrestha et al., 2005) (**Table 3),** both of which analyzed the physicochemical characteristics of wastewater during peak monsoon conditions.

Table 3. Physico-chemical characteristics of influent wastewater at GWWTP

Parameters	Unit	Nepal Standards	Design Standards of Plant (Green et al., 2003; Shah & Das, 2002)	Analysis of this study	Analysis from a previous study by (Thapa et al., 2019)	Analysis from a previous study by (S. Shrestha et al., 2005)
Temperature	°C	-	-	26.0	25.33	24.15
pH	-	6.0-9.0	-	6.88	7.32	6.9
Electrical Conductivity (EC)	µS/cm	-	-	720	1010.22	-
Total Solids (TS)	mg/L	-	-	696	-	-
Total Dissolved Solids (TDS)	mg/L	-	-	520	-	-
Total Suspended Solids (TSS)	mg/L	60	100	180	268.73	-
Turbidity	NTU	-	-	82.33	-	-

Ammonia-Nitrogen (NH_4-N)	mg/L	50	22.1	29.925	75.57	27.8
Phosphate (PO_4^{3-})	mg/L		3.2	4.78	18.03	2.95
Biological Oxygen Demand (BOD_5)	mg/L	50	25	280	281.33	182.79
Chemical Oxygen Demand (COD)	mg/L	250	250	535	996.37	351.53
BOD/COD	-	-	-	0.52	0.28	0.52

Temperature: As expected, the temperature of the wastewater sample in this study was recorded at 26.0°C, mirroring the patterns observed in previous studies. Seasonal variations play a significant role in this fluctuation, with wastewater temperatures typically being higher during the rainy season and lower during the winter months(S. Shrestha et al., 2005).

pH: The pH of the sampled wastewater was found to be slightly acidic, measuring 6.88 in this study. This is in line with the pH value of 6.9 reported by (S. Shrestha et al., 2005), but slightly lower than the pH value of 7.32 noted by (Thapa et al., 2019). The pH of wastewater is a crucial parameter affecting the efficiency of biological treatment processes, and these variations may be attributed to factors such as organic matter content and the presence of acidic or alkaline industrial effluents.

Electrical Conductivity (EC): In this study, the electrical conductivity was determined to be 720 μS/cm, indicating the presence of dissolved ions in the wastewater. While this value is lower than the 1010.22 μS/cm recorded by (Thapa et al., 2019), it still suggests the influence of various dissolved substances in the wastewater. The fluctuations in EC can be attributed to changes in ion composition, which may result from industrial discharges or natural variations.

TS, TDS, and TSS: The analysis found TS, TDS, and TSS values of 696 mg/L, 520 mg/L, and 180 mg/L, respectively. These measurements closely resemble the values reported by (Thapa et al., 2019), and demonstrate the presence of both suspended and dissolved materials in the wastewater. TSS values were slightly lower in this study compared (Thapa et al., 2019) (268.73 mg/L), indicating potential variations in the composition of suspended solids.

Turbidity: The turbidity of the wastewater is proportional to the amount of suspended and colloidal particles to which the analysis of this study reported a high turbidity of 80 NTU. The turbidity increases up to 100 NTU during the monsoon at GWWTP which could be due to the inflow of organic and inorganic matter as clay and sand mix with the wastewater (S. Shrestha et al., 2005).

Ammonia-Nitrogen and Phosphate: Nutrient levels, specifically ammonia-nitrogen and phosphate, were found to be 29.925 mg/L and 4.78 mg/L, respectively, in this study. These values align closely with the measurements reported by (S. Shrestha et al., 2005), suggesting consistent nutrient loads in the wastewater. In contrast, (Thapa et al., 2019), recorded substantially higher levels, indicating potential sources of agricultural runoff, industrial discharges, and detergent inputs during the sampling period.

BOD_5 and COD: BOD_5 and COD are key indicators of organic and chemical pollution in wastewater. The analysis done for the study revealed a BOD_5 value of 280 mg/L, similar to the levels observed in previous studies. However, the COD value was measured at 535 mg/L, while (Thapa et al., 2019) , reported a higher COD value of around 1000 mg/L. These variations can be attributed to the presence of chemical-intensive industries and hospitals discharging wastewater with elevated COD levels into the GWWTP.

BOD_5/COD Ratio: The BOD_5/COD ratio, an important parameter indicating wastewater biodegradability, was determined to be 0.52 in this study. A ratio of 0.5 or higher suggests that the wastewater is easily treatable by biological methods. In contrast, ratios below 0.3 may indicate the presence of recalcitrant or toxic components, necessitating specialized treatment approaches. The findings of this study highlight the moderate biodegradability of the wastewater influent at GWWTP.

3.2. Removal during the initiation phase

The initiation phase of the reactor occurred in a bifurcated manner, encompassing two distinct phases involving the introduction of SWW (Phase I) and the subsequent incorporation of MWW (Phase II). **Error! Reference source not found.** portrays the elimination process of key chemical parameters, namely Ammonia-Nitrogen, Phosphate, and Chemical Oxygen Demand, throughout both the adaptation phases.

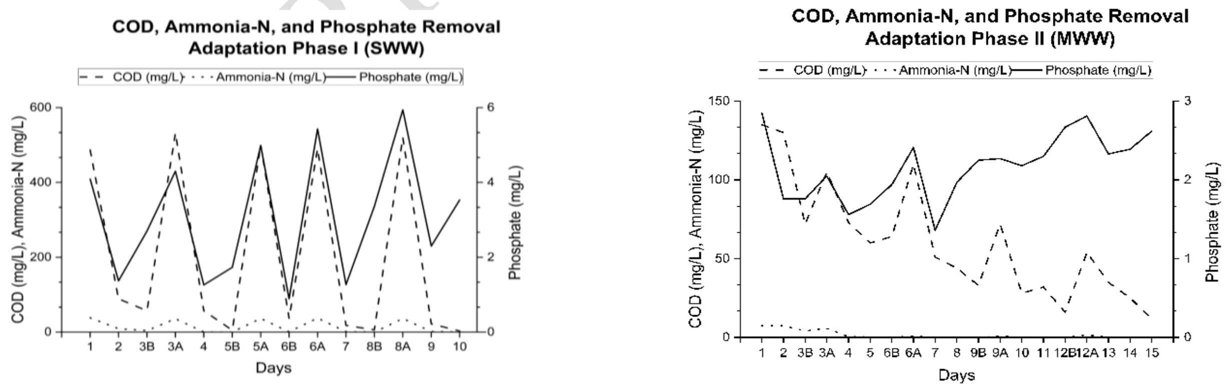

Figure 5. Removal during adaptation phase A. Phase I B. Phase II

With each introduction of a new batch of SWW, the initial concentrations of ammonia-nitrogen, COD, and phosphate exhibited a range spanning from 35.7 to 38.1 mg/L, 487 to 532 mg/L O2, and 4.09 to 5.94 mg/L, respectively. Following the initial feed, substantial ammonia-nitrogen removal rates of 76.46% and 89.37% were observed for retention times (RT) of 24 hours and 48 hours, respectively. Notably, for the subsequent four feeding events, the ammonia-nitrogen removal rates demonstrated a remarkable range between 96.48% and 99.95%. In terms of COD removal, the reactor exhibited notable efficiency, yielding removal rates of 81.72% and 88.30% within intervals of 24 hours and 48 hours, respectively, after the first feed. This impressive trend continued, with COD removal rates between 88.30% and 99.38% observed for the ensuing four feeding cycles. Similarly, phosphate removal rates following the initial feed stood at 66.50% and 33.99% for RTs of 24 hours and 48 hours, respectively. However, this trend shifted, and for the subsequent feeding episodes, phosphate removal exhibited a diverse range, spanning from 13.69% to 78.24%.

After the successful adaptation of the reactor in Phase I, Phase II involved transitioning to municipal wastewater (MWW) to facilitate the acclimatization of microorganisms to naturally occurring wastewater. For each instance of MWW introduction, the initial concentrations of ammonia-nitrogen, COD, and phosphate exhibited variability, attributed to the strategic practice of not fully draining the reactor during each new feed. Instead, a partial replacement of 1 to 2.5 liters of wastewater within the reactor was implemented. Following the initial feed, the observed ammonia-nitrogen removal rates were 0.16% and 44.64% for RTs of 24 hours and 48 hours, respectively. Subsequently, over the course of the remaining four feeding cycles, the ammonia-nitrogen removal showcased a notable range between 78.36% and 100%. In terms of COD removal, the reactor exhibited efficiencies of 3.70% and 46.67% within 24-hour and 48-hour intervals, respectively, after the first feed while, for the subsequent four feed events, COD removal rates ranged from 18.58% to 91.11%. Likewise, the phosphate removal observed after the first feed, for both 24-hour and 48-hour RTs, registered at 38.25%. Subsequently, during the successive feeds, phosphate removal displayed a range spanning from 1.40% to 52.28%. It is notable that phosphate removal demonstrated comparatively subdued performance during the adaptation Phase II.

Across both adaptation phases, it's evident that ammonia-nitrogen displayed the highest removal rate among the three chemical parameters, followed by COD, with phosphate removal being the least efficient. Importantly, during the initial feeding events, the removal efficiencies for all three parameters were comparatively lower than in the subsequent feed cycles. Additionally, it's apparent that the removal efficiencies of ammonia-nitrogen and COD exhibited an upward trend with an increase in RT, whereas phosphate removal demonstrated its maximum efficacy at an RT of 24 hours, showing a slight decrease afterward. However, it is significant that the removal rates of the analyzed chemical parameters were significantly higher during Phase I when compared to Phase II.

Upon the completion of the adaptation period in both SWW and MWW, the initial biofilm layers became observable on the internal surfaces of the PFC BIOMAX media. Concurrently, the external surfaces of the carrier media exhibited a slippery texture, as depicted in **Error! Reference source not found.** on the right. Notably, the observation of biofilm growth development on the media serves as compelling evidence that the microorganisms within the reactor have successfully acclimated to both the SWW and MWW feeds. This biofilm growth on the media surfaces validated the readiness of the reactor for subsequent phases of experimentation, demonstrating the effectiveness of the adaptation process in facilitating the development of a robust microbial community.

Figure 6. Biofilm growth during adaptation phase

3.3. Removal at different Retention Times

Following the successful acclimation and biofilm development within the reactor, an investigation was undertaken to determine the removal efficiencies of various chemical parameters. Specifically, for SWW with media, the parameters including COD, NH_4-N, and PO_4^{3-} were analyzed at varying Retention Times (RTs): 0h, 0.25h, 0.5h, 1h, 2h, 4h, 8h, 12h, 20h, and 24h. In parallel, for Municipal Wastewater (MWW), both with and without media, the removal efficiencies of COD, BOD, NH_4-N, and PO_4^{3-} were explored at distinct RTs: 0h, 0.25h, 0.5h, 1h, 2h, 4h, 8h, 12h, 20h, 24h, 48h, and 72h. The subsequent discussion provides in-depth insights into these investigations.

3.3.1. Synthetic Wastewater

Based on Error! Reference source not found., it is clear that the % removal of ammonia-nitrogen, COD, and phosphate in SWW are seen to increase with the increase in RT up to 24h. The initial

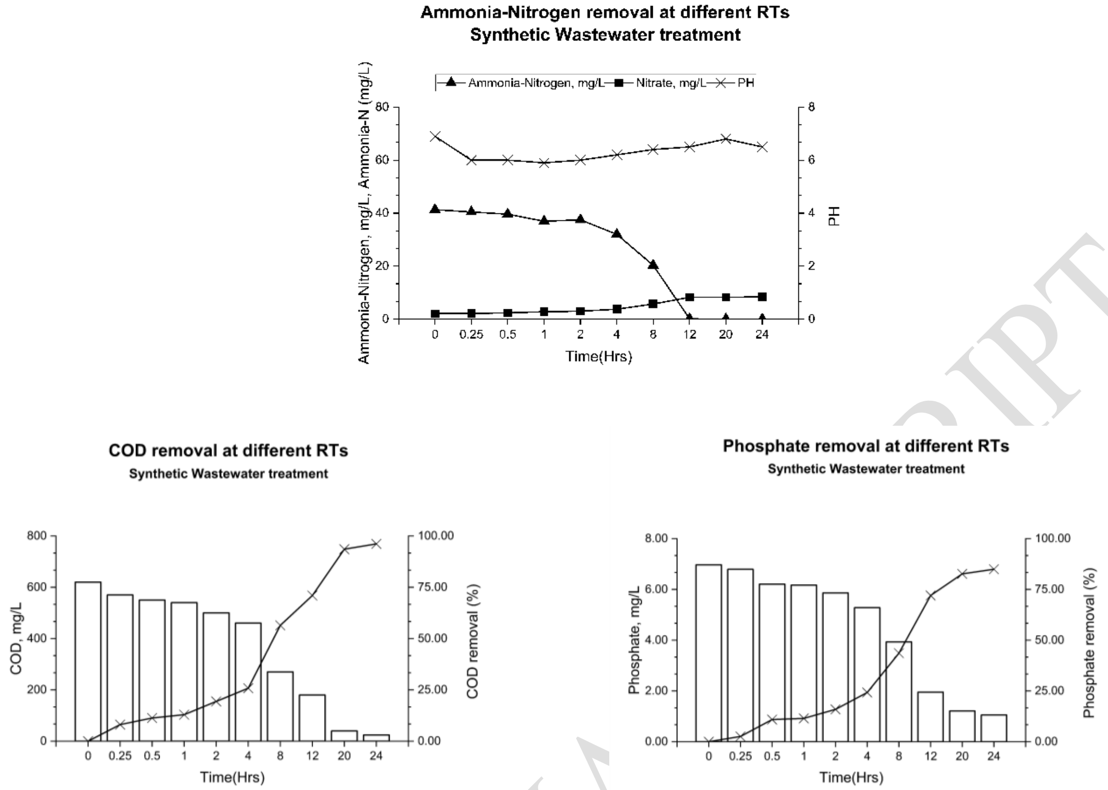

Figure 7. Removal during SWW treatment: A. Ammonia-nitrogen removal B. COD removal C. Phosphate removal

ammonia-nitrogen concentration in the SWW was 41.3 mg/L which after 24h of treatment decreased to 0.05 mg/L with a % removal of 99.88%. The graph in Error! Reference source not found.**, a)** shows the decrease in initial pH (6.9 to 5.9) up to an RT of 1h which again starts increasing gradually till 20h (5.9 to 6.8), and then again, the pH falls to 6.5 at 24h. This signifies proof of the occurrence of the nitrification process where the nitrifying bacteria converts ammonia into nitrites and then to nitrates. With the decrease in NH_4-N concentration at various RTs, there is an increase in the NO_3^- concentration. At 24h, when the NH_4-N concentration decreased from 41.3 to 0.05 mg/L, the NO_3^- concentration increased from 15.58 to 62.7 mg/L. Similarly, the initial COD in the SWW was recorded as 620 mg/L. More than 50% of the COD was removed at 8h which increased to 93.55% and 96.13% at 20 and 24h respectively. It can be observed that the removal of COD is associated with the HRT. The greater the HRT, the higher the COD removal efficiency. Even though phosphate removal was the least among the chemical parameters during the adaptation period, the % removal of phosphate at 24h was found to be 84.94% with an initial phosphate concentration of 6.97 mg/L in the SWW. It can also be illustrated from Error! Reference source not found. that the % removal of all three chemical parameters started increasing rapidly after 8h while treating SWW with media.

3.3.2. Municipal Wastewater treatment with media

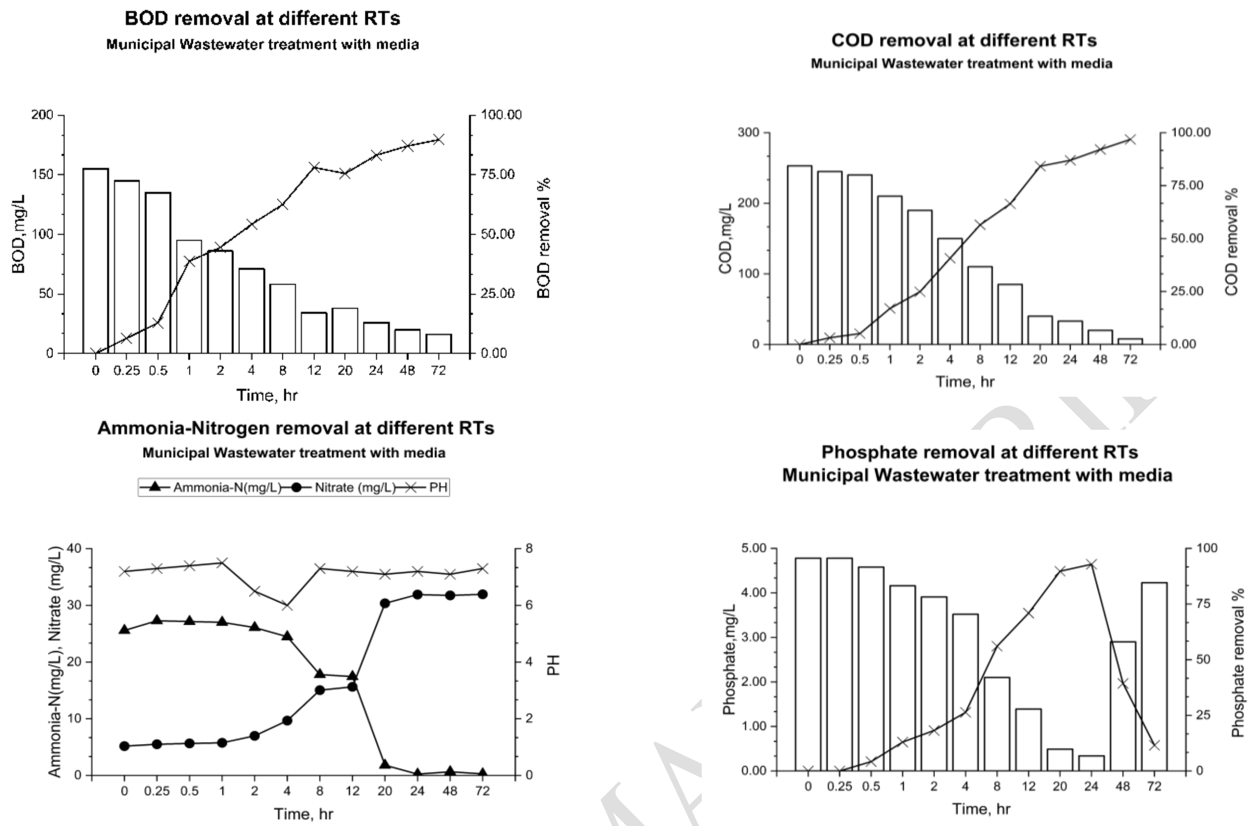

Figure 8. Removal during MWW treatment without media: a) BOD removal b) COD removal c) Ammonia-nitrogen removal d) Phosphate removal

Here, **Error! Reference source not found.** shows that the % removal of BOD, COD, and NH_4-N in MWW treatment with media increases with the increase in RT from 24 to 48 to 72h while the % removal of PO_4^{3-} increased up to 24h and decreased from 24 to 48 to 72h drastically. With MWW treatment with media, the % BOD removal at 24h was 83.23% which increased to 87.10 and 89.68% at 48 and 72 h respectively. Similarly, the initial COD in the MWW was recorded as 253 mg/L which after treatment reduced to 33 (86.96% removal), 20 (92.09% removal), and 8 mg/L (96.84% removal) at 24, 48, and 72h respectively. The A conductivity of the SWW measured at B different RTs decreased from 910 μS/cm at 0h to 690 μS/cm at 72h (24.18% removal) which supports the COD removal as the decrease in conductivity decreases the number of dissolved pollutants during the treatment. Since COD includes both organic and non-biodegradable organic components, whereas BOD exclusively comprises biodegradable organic compounds, the quantity of COD removal is always higher than the amount of BOD removal (Majid, 2019). The initial ammonia-nitrogen concentration in the MWW was 25.57 mg/L which after 24, 48, and 72h of D treatment decreased to 0.22, 0.64, and C 0.27 mg/L with a % removal of 99.14, 97.50, and 98.94% respectively. The graph in **Error! Reference source not found., c)** shows the decrease in pH after 1 to 4h (7.5 to 6) which again starts increasing and is maintained above pH

7 till 72h (6 to 7.3). This indicates the evidence for the occurrence of the nitrification process where the nitrifying bacteria converts ammonia into nitrites and then to nitrates. With the decrease in NH_4-N concentration at various RTs, there is an increase in the NO_3^- concentration. At 72h, when the NH_4-N concentration decreased from 25.57 to 0.27 mg/L, the NO_3^- concentration increased from 5.17 to 31.95 mg/L. The maximum phosphate removal during the adaptation period in MWW was 38.25% at an RT of 24h. But while treating the MWW with media at different RTs it was found that the maximum PO_4^{3-} removal was obtained at 24h with 92.89% removal with an initial PO_4^{3-} concentration of 4.78 mg/L. However, the % PO_4^{3-} removal decreased from 92.89% at 24h to 39.33 and 11.1% at 48 and 72h respectively. This declining pattern contradicts the concept that MBBR performance improves proportionally to RT until an optimum value is achieved (Abu Bakar et al., 2020). As the biological treatment processes are time-consuming, it can be seen in **Error! Reference source not found.** that the % removal of all four chemical parameters started increasing rapidly after 4h.

3.3.3. Municipal Wastewater treatment without media

As observed in Error! Reference source not found., the % removal of BOD, COD, and NH_4-N in MWW treatment without media increases with the increase in RT while there is no significant phosphate removal. With MWW treatment without media, the % BOD removal at 24h was 80.69% which increased to 86.21 and 88.97% at 48 and 72 h respectively. Similarly, the initial COD in the MWW was recorded as 257 mg/L which after treatment reduced to 57 (77.82% removal), 35 (86.38% removal), and 20 mg/L (92.22% removal) at 24, 48, and 72h respectively. The conductivity of the MWW measured at different RTs decreased from 930 μS/cm at 0h to 790 μS/cm at 72h (15.05% removal) supporting the COD removal. Because COD contains both organic and non-biodegradable organic components, but BOD only contains biodegradable organic compounds, the number of COD removed is always greater than the amount of BOD removed (Majid, 2019). The initial ammonia-nitrogen concentration before the treatment was 27.54 mg/L and after 12h of treatment, there was complete removal of ammonia-nitrogen. The graph in Error! Reference source not found., c) shows that the pH was between the range 7.3 and 7.5 till 12h which then decreases from 6.8 to 6.6. This implies the presence of a nitrification process in which nitrifying bacteria convert ammonia to nitrites and finally to nitrates. The concentration of NO_3^- increases as the concentration of NH_4-N decreases at various RTs. When the NH_4-N concentration decreased from 27.54 to 0 mg/L, the NO_3^- concentration increased from 3.15 to 36.24 mg/L. While treating the MWW without media, significant phosphate removal could not be achieved. The initial phosphate concentration in the reactor was 4.02 mg/L which decreased to 3.73 mg/L (7.21% removal) at 0.25h and after that, there were many fluctuations in the PO_4^{3-} concentrations during the treatment at different RTs.

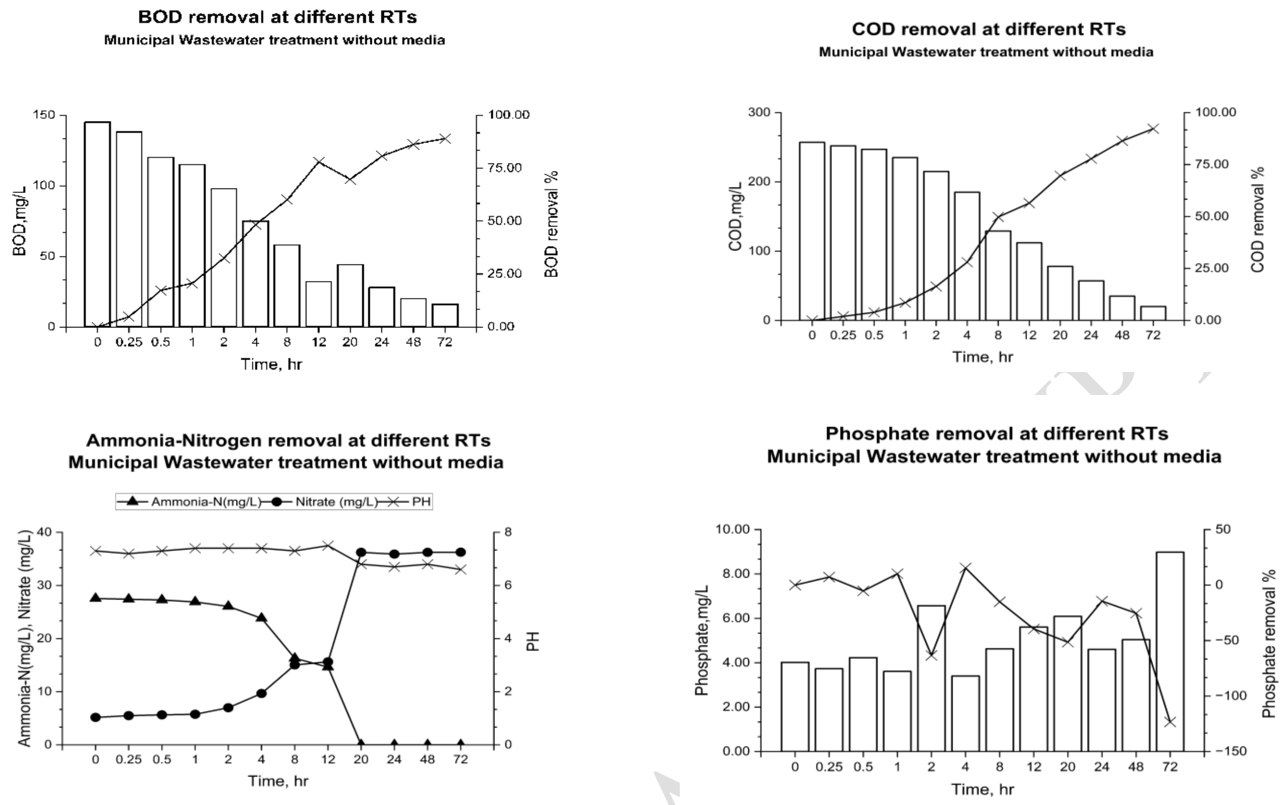

Figure 9. Removal during MWW treatment without media: A. BOD removal B. COD removal C. Ammonia-nitrogen removal D. Phosphate removal

3.4. Comparison between treatment with A B *and without media*

The treatment of municipal wastewater with and without media was carried out to have a comparative analysis between MBBR and ASP. The treatment with media would resemble an MBBR while treatment without media would act like an ASP. Hence, this comparison between treatment with and without media would provide an aid to check the feasibility of MBBR at GWWTP as the existing biological treatment unit has an ASP. Both treatments were conducted under similar operating conditions.

C D

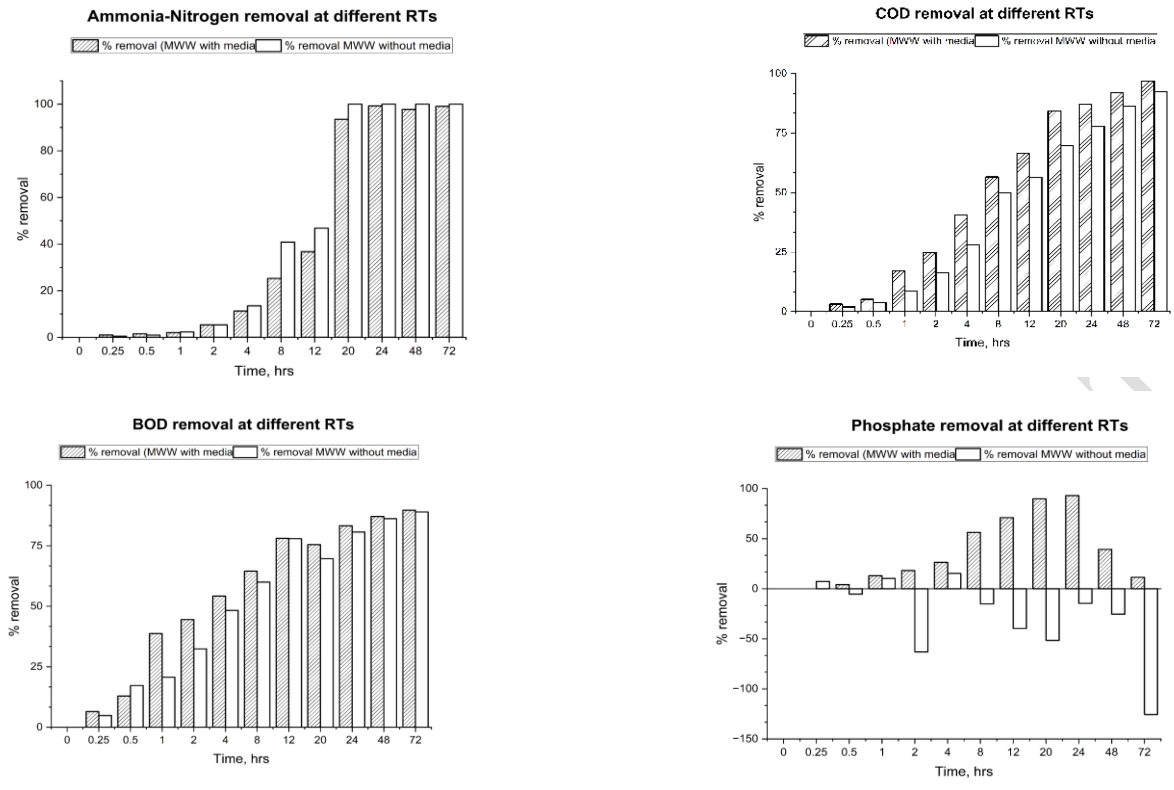

Figure 10. Removal during MWW treatment with media: A) Ammonia-nitrogen removal B) COD removal C) BOD removal D) Phosphate removal

Figure 10 depicts the comparison between the treatment of MWW with and without media for the removal of ammonia-nitrogen, COD, BOD, and phosphate. The MWW treatment without media had complete ammonia-nitrogen removal at RT of 20h and afterward. While, for the treatment with media, the highest % removal was observed as 99.20% at 24h. The treatment with media had slightly greater removal till RT of 1h which was surpassed by the treatment without media right after RT of 1h. COD removal increased with an increase in RT for both treatments. However, MWW treatment with media had a comparatively greater % removal of 96.84 at 72h than treatment without media which had a removal of 92.22% at 72h. Similarly, BOD removal also increased with an increase in RT for both treatment with and without media and had similar removal efficiencies of 89.68 and 88.97% respectively. The treatment with media had a significant phosphate removal of 92.98% at 24h. Until 24h, the phosphate removal increased with the increase in RT which then drastically decreased at RT of 48 and 72h. Contrarily, the treatment without media could not achieve significant phosphate removal as there were many fluctuations in the phosphate concentrations during the treatment at different RTs.

3.5. Findings and Insights

The Moving Bed Biofilm Reactor (MBBR) is a cutting-edge and innovative approach for treating urban and industrial wastewater. MBBR overcomes issues such as sludge bulking, foaming, inadequate sludge settling, and carrier clogging. Importantly, MBBR provides significant advantages such as ease of operation, which is driven by attributes such as exceptional impact resistance and the absence of sludge return requirements (Javid et al., 2013). Furthermore, the system demonstrates robustness against perturbations. including pH fluctuations, elevated COD levels, and high temperatures (Zhou et al., 2018).

During this study, the treatment process was carried out in a laboratory-scale batch Moving Bed Biofilm Reactor (MBBR) configuration, with experimental runs undertaken both with and without a media. The inclusion of treatment without media condition was particularly insightful, as it closely emulated an Activated Sludge Process (ASP), enabling a more straightforward comparison of removal efficiencies between MBBR and ASP. This comparative approach was pertinent due to the presence of an existing ASP-based biological treatment unit at the Guheshwori Wastewater Treatment Plant (GWWTP), whereas this investigation aimed to explore the viability of implementing MBBR at the Guheshwori Wastewater Treatment Plant. The study's primary objective was to evaluate system performance by examining of BOD, COD, ammonia-nitrogen, and phosphate removal. These assessments were carried out at various Retention Times (RTs), encompassing the phases of microorganism adaptation and their subsequent colonization on the carriers.

Based on the findings of this study, it was determined that both treatment approaches, employing media and without media, yielded comparable BOD removal rates of 89.68% and 88.97%, respectively, when subjected to a Retention Time (RT) of 72 hours. Similarly, the treatment with media removed more COD than the treatment without media. In contrast media-free treatment exhibited expedited and complete ammonia-nitrogen removal, which intriguingly contradicts the historical performance of the GWWTP, which recorded minimal ammonia-nitrogen removal at 29.11% (Thapa et al., 2019). Similarly, the treatment approach incorporating media displayed a commendable ammonia-nitrogen removal efficiency of 99.20% within 24 hours. Notably, the media-based treatment outperformed the media-free strategy in terms of phosphate removal.

4. Conclusion and Recommendations

After studying and interpreting the results, it is clear that the Moving Bed Biofilm Reactor (MBBR) is a very efficient method of eliminating BOD, COD, ammonia-nitrogen, and phosphate from municipal wastewater. The noteworthy element is that MBBR may accomplish this efficacy while having a lower tank footprint than the Activated Sludge Process (ASP), which requires bigger tank dimensions. This essential feature distinguishes MBBR as a unique and cost-effective treatment technology, putting it apart from traditional options.

Implementing MBBR at GWWTP provides significant environmental benefits, including improved wastewater treatment efficiency, reduced organic and nutrient contamination, and restoration of the Bagmati River ecosystem. However, effective system design, monitoring, and integration with other treatment methods are required to address plastic pollution, non-renewable energy dependence, and other emissions. The MBBR frequently experiences operational issues because to media clogging and aeration deficiencies. It also faces economic limits because to high capital and operational expenses, as well as environmental concerns such as sludge, plastic waste, and emissions.

MBBR works alongside other sustainable wastewater treatment methods, such as artificial wetlands, to lower other nutrients (e.g., phosphorus, nitrogen, etc.) and pathogens before discharging the effluent for irrigation. Anaerobic digestion turns high sludge from MBBR into renewable biomass. The report proposes that MBBR be compatible with other sustainable measures. The implementation of MBBR is consistent with various Sustainable Development Goals (SDGs), including clean water and sanitation (SDG 6), sustainable cities (SDG 11), and sustainable production (SDG 12).

It enhances safe water discharge into rivers, helps to build resilient urban wastewater systems, and promotes resource recovery in accordance with circular economy concepts. With its numerous advantages over traditional technologies, MBBR appears as a viable alternative for wastewater treatment in new wastewater treatment plant (WWTP) projects or under construction WWTPs. This is especially important in developing nations like Nepal, where MBBR's cost-effective methodology and exceptional features have great potential.

Acknowledgement

I would to express my deepest gratitude to my PhD supervisor Professor Dr. Sateesh Kumar Ojha for his invaluable encouragement and support thorough this journey. I am also immensely grateful to him for his constructive advice, technical support, and inspiration.

I would like to extend my thanks to my colleagues and lab members at Lincoln University College and in Case Study Area (Kathmandu Nepal) for their collaboration.

References

Abu Bakar, S. N. H., Abu Hasan, H., Mohammad, A. W., Abdullah, S. R. S., Ngteni, R., & Yusof, K. M. M. (2020). Performance of a laboratory-scale moving bed biofilm reactor (MBBR) and

its microbial diversity in palm oil mill effluent (POME) treatment. *Process Safety and Environmental Protection*, *142*, 325–335. https://doi.org/10.1016/j.psep.2020.05.004
Biswas, K., Taylor, M. W., & Turner, S. J. (2014). Successional development of biofilms in moving bed biofilm reactor (MBBR) systems treating municipal wastewater. *Applied Microbiology and Biotechnology*, *98*(3), 1429–1440. https://doi.org/10.1007/s00253-013-5082-8
Cao, C. Y., & Zhao, Y. H. (2012). The comparison of MBBR and ASP for treatment on petrochemical wastewater. *Petroleum Science and Technology*, *30*(14), 1461–1467. https://doi.org/10.1080/10916466.2010.506458
Flemming, H. C., Wingender, J., Szewzyk, U., Steinberg, P., Rice, S. A., & Kjelleberg, S. (2016). Biofilms: An emergent form of bacterial life. In *Nature Reviews Microbiology* (Vol. 14, Issue 9, pp. 563–575). Nature Publishing Group. https://doi.org/10.1038/nrmicro.2016.94
Green, H., Poh, S.-C., & Richards, A. (2003). *Wastewater Treatment in Kathmandu, Nepal*.
Javid, A. H., Hassani, A. H., Ghanbari, B., & Yaghmaeian. (2013). Feasibility of Utilizing Moving Bed Biofilm Reactor to Upgrade and Retrofit Municipal Wastewater Treatment Plants. *Int. J. Environ. Res*, *7*(4), 963–972.
KUKL. (2013). *Initial Environmental Examination NEP: Kathmandu Valley Wastewater Management Project*.
Majid, A. (2019). Application of Lab-Scale MBBR to Treat Industrial Wastewater using K3 Carriers: Effects of HRT, High COD Influent, and Temperature. *International Journal of Environmental Sciences & Natural Resources*, *20*(2). https://doi.org/10.19080/ijesnr.2019.20.556031
Mateo-Sagasta, J., Raschid-Sally, L., & Thebo, A. (2015). Global wastewater and sludge production, treatment and use. In *Wastewater: Economic Asset in an Urbanizing World* (pp. 15–38). Springer Netherlands. https://doi.org/10.1007/978-94-017-9545-6_2
Porsgaard, H., & Soderstrom, S. (2015). *Removal of Nitrogen from Landfill Leachates with MBBR and SBR A Pilot Study at the Brudaremossen Landfill* [Division of Water Environment Technology]. CHALMERS UNIVERSITY OF TECHNOLOGY.
Ramtel, P., Tamang, T., Pokhrel, N., Mainali, B., & Paudel, S. R. (2021). *Environmental Engineering and Management* (Vol. 20, Issue 2). http://www.eemj.icpm.tuiasi.ro/;http://www.eemj.eu
Regmi, S. (2013). *Shakil Regmi WASTEWATER TREATMENT IN KATHMANDU Management, Treatment and Alternative Environmental Engineering Wastewater Treatment in Kathmandu*.
Renou, S., Givaudan, J. G., Poulain, S., Dirassouyan, F., & Moulin, P. (2008). Landfill leachate treatment: Review and opportunity. In *Journal of Hazardous Materials* (Vol. 150, Issue 3, pp. 468–493). https://doi.org/10.1016/j.jhazmat.2007.09.077
Shah, R. D., & Das, S. K. (2002). *Performance of deep oxidation ditch Shah Ram Deep and Das Sunil Kumar, Nepal SUSTAINABLE ENVIRONMENTAL SANITATION AND WATER SERVICES*.
Shrestha, N., Regmi, R. K., & Mishra, B. K. (2015). *Water and Urban Initiative Current Status of Water Environment in Kathmandu Valley, Nepal*.
Shrestha, S., Deshar, R., Pandey, S., & Joshi, G. R. (2005). EFFICIENCY OF THE WASTEWATER TREATMENT AT GUHESHWORI, KATHMANDU VALLEY. *Journal of Stratigraphic Association of Nepal (SAN)*, *5*, 25–33.
Thapa, B., Khatiwada, N. R., Ghimire, A., Adhikari, B., & Badaila, R. (2019). *Study on Kinetics of Pollutants Removal in Guheshwori Wastewater Treatment Plant, Kathmandu*. http://www.imedpub.com/journal-water-pollution-control/
Timilsina, B. (2010). *A-Case-Study-Of-Kathmandu-Valley-Nepal-Partial-fulfillment-of-GUS-UNITAR-Training*.
UN. (2018). *World Urbanization Prospects The 2018 Revision*.
UNDP Nepal. (2022). *Nepal moves up one place in human development, ranks 143rd*.

UNESCO. (2017). *Wastewater: the untapped resource: the United Nations world water development report 2017*. United Nations Education, Scientivic and Cultural Organization. https://doi.org/https://doi.org/10.18356/df181e6f-en

Yang, L., Li, H. Q., & Yang, P. (2018). Evaluation of different structures of moving bed biofilm reactors (MBBR) for synthetic wastewater treatment. *IOP Conference Series: Earth and Environmental Science*, *167*(1). https://doi.org/10.1088/1755-1315/167/1/012009

Zhou, H., Wang, G., Wu, M., Xu, W., Zhang, X., & Liu, L. (2018). Phenol removal performance and microbial community shift during pH shock in a moving bed biofilm reactor (MBBR). *Journal of Hazardous Materials*, *351*, 71–79. https://doi.org/10.1016/j.jhazmat.2018.02.055

Zhu, Y., Zhang, Y., Ren, H. qiang, Geng, J. ju, Xu, K., Huang, H., & Ding, L. li. (2015). Physicochemical characteristics and microbial community evolution of biofilms during the start-up period in a moving bed biofilm reactor. *Bioresource Technology*, *180*, 345–351. https://doi.org/10.1016/j.biortech.2015.01.006