ZIBELINE INTERNATIONAL™ PUBLISHING

Water Conservation & Management (WCM)

DOI: http://doi.org/10.26480/wcm.04.2025.648.654

ISSN: 2523-5664 (Print)
ISSN: 2523-5672 (Online)
CODEN: WCMABD

CrossMark

RESEARCH ARTICLE

ENHANCING BIOFILM GROWTH IN MOVING ATTACHED GROWTH TECHNOLOGIES FOR WASTEWATER TREATMENT

Manish Kumar[a], Dayanand Sharma[b]

[a]Department of Civil Engineering, Sharda University, Greater Noida- 201310
[b]Department of Civil Engineering, Sharda University, Greater Noida- 201310
****Corresponding Author Email: dayanandsvnit@gmail.com***

Article History:

Received 11 June 2025
Revised 21 July 2025
Accepted 17 August 2025
Available online 11 September 2025

ABSTRACT

The study addresses the prolonged start-up phase in Moving Bed Biofilm Reactors (MBBRs), a key limitation that hampers the widespread adoption of biofilm-based wastewater treatment technologies despite their high efficiency in removing nitrogen and organic pollutants. This delay is primarily due to the slow establishment of biofilms on carrier media. To overcome this, a pilot-scale study was conducted to evaluate the influence of carrier media physical properties—shape, density, voidage, and hydraulic efficiency—on biofilm development using real municipal wastewater. The system, comprising anaerobic, anoxic, and aerobic zones, was operated over 90 days with four different media types, each with distinct geometrical and surface area characteristics. Results showed that spherical carriers with higher voidage and lower density promoted significantly faster biofilm growth, achieving stable biofilm accumulation in 35–45 days. Media 2, a cylindrical type, achieved the highest attached biomass at 10.12 g TS/m^2 and a biofilm growth rate of 10.12 g TS/m^2/day, while Media 1 (spherical) demonstrated enhanced start-up dynamics due to its superior hydraulic properties despite lower total surface area. COD and BOD$_5$ removal efficiencies improved correspondingly, achieving effluent concentrations as low as 18–20 mg/L (COD) and 4–7 mg/L (BOD$_5$). The study suggests that traditional measures that rely only on the percentage of protected surface are inadequate. Rather, a composite variable—diameter-to-void ratio divided by hydraulic efficiency—better over hydraulics than predicts biofilm performance. The work described in this study demonstrates a new method for assessment of the carrier media effectiveness, which can be readily utilized as a tool for minimizing the MBBR start-up time, optimizing the media design and improving the scalability of moving biofilm systems for sewage treatment.

KEYWORDS

Aerobic zones, Anaerobic, Anoxic, Biofilm accumulation, BOD$_5$ (Biochemical Oxygen Demand, 5-day), COD (Chemical Oxygen Demand), MBBR (Moving Bed Biofilm Reactor), NH_4^+-N (Ammonium Nitrogen)

1. INTRODUCTION

The increasingly strict regulations on the outlet of effluent into the environment make it urgent to develop highly efficient, green, and compact water and wastewater treatment approaches. Among these, biofilm-based processes, such as the Moving Bed Biofilm Reactor (MBBR) have been worldwide spread as applicable treatment means resulting in higher treatment capability, operational temperance and lower space requirement compared to conventional activated sludge processes (Prasad et al., 2021; Regmi et al. 2011). MBBRs are based on mobile carrier media in suspension in the reactor volume, their mobility inside the reactor has a direct effect on biofilm growth which makes possible high biomass retention therefore high nutrient removal capacity with fluctuating hydraulic and organic load conditions (Alitaleshi et al., 2024; Madan et al., 2022).

However, despite these merits, one of the principal challenges of applying MBBR technology to the full-scale operation is the extended start-up time, invariably ranging from several weeks to few months depending on the type of carrier used, wastewater characteristics and operational conditions (Jagaba et al., 2024). The starting-up phase, which is the period necessary to develop a stable and active biofilm layer, is essential for the identification of process sustainability, particularly in context of plant up-gradation or intermittent operations (Gzar et al., 2021). Biofilm formation starts with primary attachment of the microbial cells to the carrier surface, then secretion of extracellular polymeric substances (EPS) and colonization and thickening of the biofilm matrix (Di Trapani et al. 2008).

It has been documented in many works that the properties of the carrier media—shape, surface roughness, density, porosity, hydrophobicity and surface area— will be the main factors determining the biofilm growth kinetics (Sharma et al., 2024; Falletti et al., 2014). However, the conventional design and selection of carriers have historically been based on a single parameter -the protected surface area (m^2/m^3) and may not fully represent the rather complex hydrodynamic and microbial conditions during start-up. High surface area will not only enhance potential for attachment, but could also increase shear stress and clogging potential, especially in the presence of fluid turbulence (Dias et al., 2018). Therefore, understanding the multi-parameter interplay between carrier geometry and reactor hydraulics is vital to optimizing biofilm formation and shortening start-up durations. Additionally, the nature of the wastewater, including its organic loading, ammoniacal nitrogen (NH_4^+-N) content, C:N ratio, and biodegradability, significantly influences microbial community development and biofilm characteristics (Zhuang et al., 2019). Most prior investigations into biofilm start-up have been carried out using synthetic wastewater in laboratory-scale setups with low variability in

Quick Response Code	Access this article online	
	Website: www.watconman.org	**DOI:** 10.26480/wcm.04.2025.648.654

influent composition (Dereli et al., 2021). These controlled environments, while beneficial for mechanistic insights, may not reflect the performance of MBBRs under real-world, fluctuating wastewater conditions encountered in municipal settings. As a result, there is a substantial knowledge gap concerning the start-up behavior of MBBRs using actual municipal wastewater, particularly in pilot or full-scale systems (Jagaba et al. 2024). Moreover, operational strategies such as media filling ratio, aeration intensity, hydraulic retention time (HRT), and internal recirculation influence the shear forces acting on developing biofilms, affecting both attachment and detachment rates (Xu et al., 2025). Studies have shown that biofilm detachment is primarily driven by hydrodynamic shear and inter-media collisions, emphasizing the need for mechanical and process design optimization (Wang et al., 2022). Similarly, redox stratification achieved via the configuration of anaerobic, anoxic, and aerobic zones enhances nitrogen removal through sequential nitrification-denitrification but requires careful control of DO and ORP levels for stable microbial activity (Zhu et al., 2015).

Recent advancements in surface modification technologies, such as plasma treatment, chemical grafting, or 3D printing, have enabled the tailoring of carrier surfaces to promote microbial adhesion and selective biofilm enrichment (Bassin et al., 2016). However, these approaches often focus on enhancing long-term process stability rather than reducing start-up time. As a result, the relationship between media geometry and biofilm start-up dynamics remains underexplored, particularly in systems handling complex wastewater matrices with high nitrogen and organic loads.

The present study addresses this gap by investigating the effect of physical properties of four different carrier media—with varying shapes, surface areas, densities, and voidages—on biofilm development and start-up kinetics in a pilot-scale moving attached growth system treating real municipal wastewater. The experimental setup comprises a three-stage (anaerobic-anoxic-aerobic) reactor configuration with a controlled internal recycle to simulate biological nutrient removal (BNR) conditions. The start-up period is quantitatively evaluated based on biofilm accumulation (g TS/m^2), COD and BOD$_5$ removal efficiency, and ammonia elimination, all measured under consistent organic and ammonia loading rates normalized by carrier surface area. By correlating the biofilm growth rate with a derived dimensionless parameter involving media diameter, voidage, and hydraulic efficiency, the study proposes a novel design criterion that goes beyond the conventionally used protected surface area metric. Moreover, the findings provide empirical support on how carrier dimensions influence the process hydrodynamics, biomass retention and nutrient removal, and hence a sound basis in which to optimize media selection and reactor start-up regimes for MBBR processes. This paper provides insight for the design of full-scale plants based on MBBR process to save commission time, minimize operating cost, and improve long-term system reliability.

2. Material And Methods

2.1 Pilot Plant Setup And Operation Conditions

To assess the influence of the carrier media characteristics in biofilm formation and system start-up, a pilot-scale Moving Bed Biofilm Reactor (MBBR) was built. The process consisted of three biological reactors, i.e., anaerobic, anoxic and aerobic, as well as a settling unit that can be considered as a Modified Ludzack–Ettinger (MLE) design adapted for biological nutrient removal (BNR) in figure 1. The reactors were transparent and made of acrylic to allow for visual inspection. The anaerobic and anoxic tanks had the same size (150 mm × 150 mm × 500 mm), and the aerobic tank had a larger size (200 mm × 200 mm × 500 mm) due to the need for aeration apparatus. The inlet and outlet of each tank was fitted with baffles in order to improve flow distribution and to reduce the dead zone. Flow rate at 100 liter/day was operated daily with hydraulic retention time (HRT) at around 6–8 hours, same with full-scale application (Xu et al., 2025). Aeration was given in the aerobic tank by aerators covering with medium bubble diffusers and a controlled DO level was maintained from 1.5 to 2.0 mg L-1 (HACH, USA) by a portable DO meter. Redox potential (ORP) was controlled in each zone in order to obtain adequate redox stratification: −100 to −250 mV in the anaerobic tank, +50 to −50 mV in the anoxic tank and, +150 to +250 mV in the aerobic tank. The internal recycle between aerobic and anoxic tanks was kept up to 400% relative to influent using a submersible pump, while 50% recycling between the settling tank and the anaerobic tank was maintained for sludge return. These control parameters resulted in stable operation and effective multiple-nitrogen transformation by zones (Wang et al., 2022). The reactor was inoculated with RAS from the secondary clarifier of Municipal Sewage Treatment plant of Delhi (DJB), and in both compartments the MLSS (mixed liquor suspended solid) was approximately 3000 mg/L. In the investigation of the influence of carrier properties on the start-up, four different media were examined consecutively (Media 1 to 4, total of 90 days), each of them cultured for about 22–23 days. All media were filled up to 30% of the reactor volume, as required by design guidelines and their characteristics are reported in table 1 (Zhu et al., 2015).

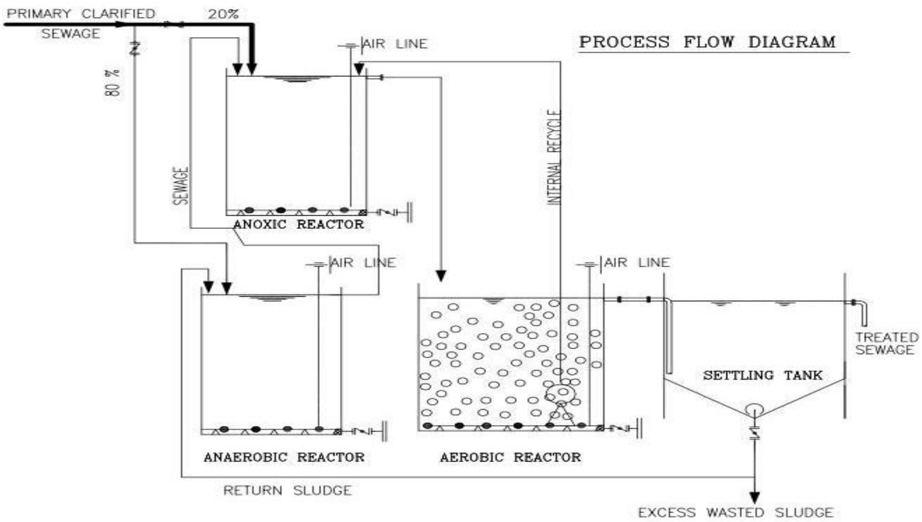


Figure 1: Process flow diagram for pilot plant for treatment of wastewater.

Figure 1 illustrates the overall process flow, with separate lines for influent division, return sludge, and internal nitrate recycling. Influent wastewater was drawn from the primary clarifier of the DJB plant, with 80% fed to the anaerobic tank and 20% to the anoxic tank, following a split-flow BNR configuration to enhance denitrification efficiency (Bassin et al., 2016). This setup allowed the evaluation of biofilm development across carriers with varied surface geometry, density, and voidage, thereby providing insights into how carrier design influences microbial colonization and start-up kinetics in a realistic wastewater environment.

2.2 Chemical Analysis

Daily sampling and complete chemical analysis were used to assess the performance of the system after start-up and for monitoring biofilm formation on the various examined carrier materials. The study primarily aimed to quantify organic matter, nutrient content, and biofilm biomass in influent and effluent streams of the pilot MBBR installation. Daily samples of wastewater were taken from the influent and effluent points of the reactor system. All analysis was done in accordance with the procedures described in the Standard Methods for the Examination of Water and Wastewater (APHA, 2005). Parameters from the study were 5-day biochemical oxygen demand (BOD$_5$), chemical oxygen demand (COD), total suspended solids (TSS), ammoniacal nitrogen (NH_4^+-N), total nitrogen (TN), and total phosphorus (TP). These variables were chosen in order to determine the efficiency of removal of carbon and nutrient of the system through various conditions of operation. Temperature, pH, and DO on site were measured by portable multi-parameter meters (HACH, UK). Samplings were obtained daily, at the same time, in order to provide comparable and precise monitoring of the reactor stability. The dissolving oxygen was specially controlled in aerobic zone to keep the optimal situation for nitrifying and hetero-trophic bacteria populations. The biofilm growth on the carrier media was determined gravimetrically following the procedure was adopted (Regmi et al. 2011). Carriers were collected on a daily basis from the aerobic reactor zone in a representative and random manner. Following completion of tests all carrier samples were washed delicately with distilled water in order to detach loosely adsorbed particulates. The washed media were dried in the oven at 105°C for 24 h to determine the dry weight. Biofilms were then removed by physical shaking and chemical immersion (if required), and the carriers were re-dried. The biomass attached was calculated as the dry weight of the carriers after biofilm removal subtracted from the weight of the dry carriers before biofilm removal divided by the protected surface area of the media. The resulting number was then given in g TS/m^2 (total solids per m^2 of surface area of carrier). Surface organic and ammonia loading rates were adjusted for each media type by influent concentrations and protected surface area to maintain the same loading conditions. These loadings can then be normalized such that biofilm growth dynamics and system performance can be fairly compared among the four media configurations. Software IBM SPSS Statistics was then adopted to perform statistical analysis. The collected data were checked for normality using the Shapiro–Wilk test, and one-way analysis of variance (ANOVA) was used to statistically contrast parameters behavior amongst the media types at 95% confidence interval ($p < 0.05$). All instruments were calibrated before each determination was made, and reagent grade chemicals were used to guarantee the accuracy and precision of the analyses.

Table 1: Media characteristics used in this study

S.No.	Media	Total surface (m²/m³)	Shape	Dimensions		Material	Density (g/cm³)
				Length (mm)	Diameter (mm)		
1.	(Biochip)	5500	Circular	1.25	32	Polypropylene	0.92
2.	White 12*25	350	Cylindrical	25	12	Polypropylene	0.92
3.	White 16*22	400	Cylindrical	22	16	Polypropylene	0.92
4.	Black 16*22	400	Cylindrical	22	16	HDPE	0.97

3. Results And Discussion

This section presents and analyzes the biofilm formation dynamics and treatment performance of the pilot-scale moving attached growth system using four different types of carrier media. The discussion is structured around the influence of media geometry, surface area, hydrodynamics, and loading conditions on start-up behavior and pollutant removal efficiencies. Figures 1 and Graphs 1–5, as well as Tables 1 and 2, serve as the basis for the discussion.

3.1 Process Stability and Operational Conditions

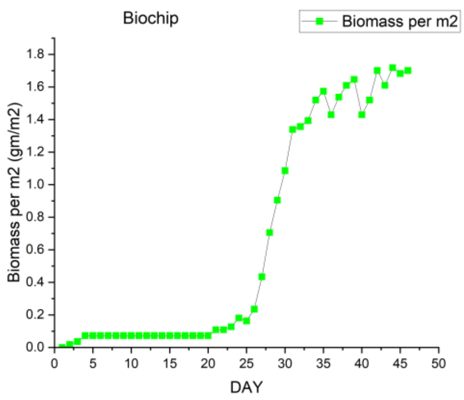
The pilot plant was operated under stable conditions with effective redox stratification maintained in the anaerobic, anoxic, and aerobic compartments. As depicted in Figure 1, the internal recirculation (400%) and return sludge (50%) facilitated effective mixing and nutrient redistribution, ensuring a balance between carbon oxidation, nitrification, and denitrification processes. Table 2 summarizes the physicochemical characteristics of the influent wastewater during each media trial. Influent COD levels ranged between 241 and 419 mg/L, BOD_5 between 98 and 112 mg/L, and ammoniacal nitrogen between 28 and 37 mg/L. These values reflect typical municipal sewage composition and align with those reported in previous studies using real wastewater, such as (Alitaleshi et al. 2024), who documented COD between 350–450 mg/L and NH_4^+-N around 30 mg/L in pilot MBBRs. Temperature variation between 20.7°C and 22.3°C throughout the trials was minimal and did not significantly influence microbial activity, as this range falls within the optimal window for mesophilic biofilm systems (Ødegaard 2006).

Table 2: Characterization of the wastewater fed to the pilot plant operated with different media during start up.

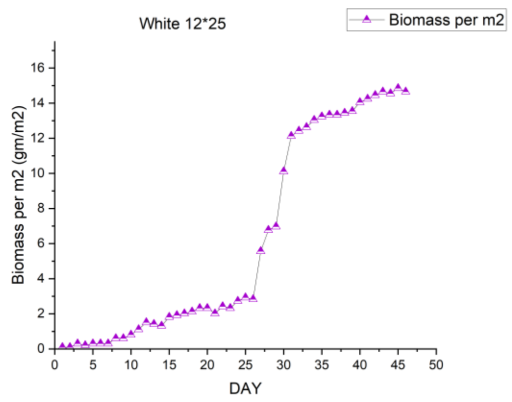
Parameter	Unit	Media 1	Media 2	Media 3	Media 4
pH		7.18±0.10	7.2±0.11	7.07±0.11	7.08±0.10
COD	mg/l	308±232	294±112	241±149	296±212
BOD	mg/l	99.4±93.6	98±35	99±36	112±79
TSS	mg/l	103±205	156±56	159±58	103±196
Ammonia (NH_4^+N)	mg/l	28±6	28±6	28±6	28±6
TP	mg/l	4.2±2.6	4.2±1.4	3.0±3.8	4.2±1.4
TN	mg/l	32.4±13.2	36±10	32.4±13.8	36.4±8.4

3.2 Comparative Analysis of Biofilm Accumulation

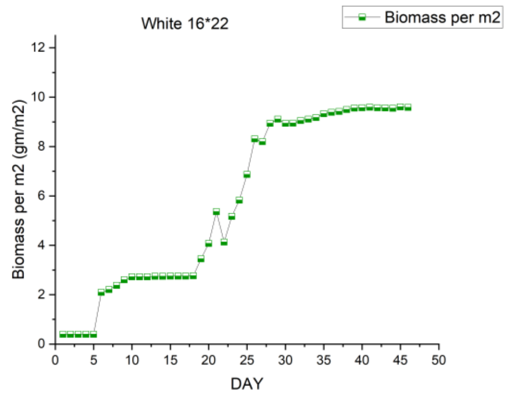
The temporal evolution of biofilm biomass on carrier surfaces was monitored throughout the start-up period, and the results are visualized in Graphs 1 to 4. Biofilm accumulation was quantified as g TS/m^2, with differences attributed to carrier geometry, surface area, density, and voidage, as specified in Table 1. Media 2 (White cylindrical, 12×25 mm, surface area 350 m^2/m^3) exhibited the fastest and highest biofilm accumulation, stabilizing at 10.12 g TS/m^2 by day 45. This performance significantly exceeded that of Media 3 (White cylindrical, 16×22 mm, 8.51 g TS/m^2), Media 4 (Black cylindrical HDPE, 6.16 g TS/m^2), and Media 1 (Biochip circular, 1.10 g TS/m^2), despite Media 1 having the highest theoretical surface area (5500 m^2/m^3). These findings suggest that excessive surface area, as in Media 1, may lead to lower hydraulic efficiency and shear instability, inhibiting stable biofilm development—a trend similarly noted by (Ødegaard 2006) and (McQuarrie and Boltz 2011). The superior performance of Media 2 can be attributed to its optimal shape, diameter, and voidage, which promoted favorable hydrodynamics and enhanced biomass retention.



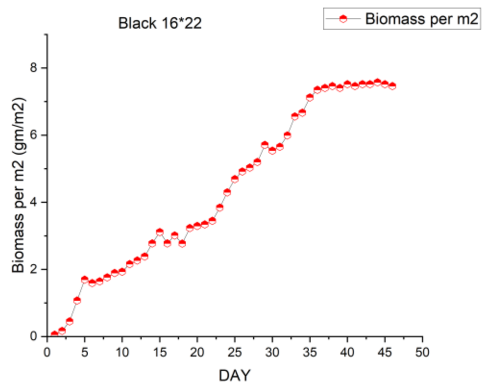
Graph-1: Biomass growth for Biochip media-1



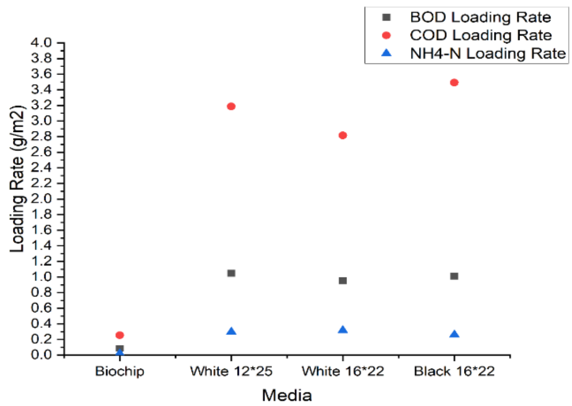
Graph-2: Biomass growth for White media-2



Graph-3: Biomass growth for White media-3



Graph-4: Biomass growth for Black media-4



Graph-5: (BOD/COD/Nh4-N) Loading rate for media-1,2,3 & 4

Figure 2: Variations of media with different parameters

3.3 Start-up Duration and Biofilm Growth Rates (Graphs 1–4)

The initiation period for colonization of the system was considered to be the time for biofilm growth until a steady-state was achieved. According to the daily biomass recorded (Graph 1- 4), steady development of the biofilm reached from 35 to 45 days in all the media studied, with different rates of growth. The calculated biofilm formation rate was the greatest in Media 2 (10.12 g TS/m^2/day) followed by Media 3 (5.75 g TS/m^2/day), Media 4 (4.30 g TS/m^2/day) and Media 1 (0.65 g TS/m^2/day). The relationships between media properties and start-up kinetics are consistent with the results of that microbial adhesion and EPS production was increased in round or semi-suspended media with high surface roughness during the initial colonization phase (Prasad et al., 2024; Gupta et al., 2023). Notably, the low performance of Media 1 compared to its ultrahigh surface area is consistent with the findings of who described that too large biochip-type carriers suffers from shear detachment due to turbulence-induced media collision (Prasad et al., 2023; Regmi et al., 2011).

3.4 Influence of Organic and Ammonia Loading on Biofilm Stability

The correlation between loading rates and biomass accumulation is shown in Graph 5, where BOD_5, COD and NH_4^+-N was recorded against specific biofilm densities. In all media, there was a trend that the higher the organic and ammonia loading rate (g/m^2·day), the stronger the biofilm growth. Media 2 and Media 3, which had loading rates of 3.18 and 2.81 g COD/m^2·day respectively, developed significantly higher biomass than Media 1, which had a lower COD loading of 2.4 g COD/m^2·day despite its large surface area. Ammonia loading also influenced nitrifying biofilm enrichment. Media 2 and 3, with NH_4^+-N loading around 0.297–0.315

g/m²·day, achieved higher biomass densities than Media 1 (0.019 g/m²·day), consistent with the findings of who emphasized that stable ammonia loading during start-up is essential for enriching autotrophic communities (Zhu et al., 2015).

3.5 Carrier Shape and Hydraulic Efficiency as Predictors of Biofilm Growth

The results support the hypothesis that protected surface area alone is insufficient to predict media performance. Instead, a composite indicator incorporating media diameter (Di), voidage (Voi), and hydraulic efficiency (HE)—represented as (Di × Voi)/HE—provides a better correlation with biofilm development and pollutant removal kinetics. This finding builds upon the work of Dias et (Falletti et al. 2014), who highlighted the need to integrate geometric and fluid dynamic properties in media selection. Media 2, with its optimal combination of moderate diameter and high voidage, outperformed high-density or oversized carriers by achieving a favorable shear environment conducive to microbial adhesion and growth.

3.6 Comparison with Previous Studies and Implications for Full-Scale Applications

Compared to previous laboratory and pilot trials, the regular run of the experiment showed good start-up performance. This study, demonstrated steady biofilm growths of 20–30 days with chip type polyethylene media with high surfaced area, whereas reached start-up in 6 days only using modified spherical media and increased hydraulic retention (Regmi et al., 2011; Falletti et al., 2014). Yet, these researches were performed on synthetic wastewater, with enriched inocula, in contrast to this study that was carried out with real urban wastewater and operational conditions. The observed biofilm densities (6–10 g TS/m² for Media 2–4) were also in good agreement with the values, where steady-state amount of biomass between 11.5–15 g TS/m² were observed under similar volumetric loading and fill factors (Zhuang et al., 2019). Consequently, the results from this analysis confirm that the scale-up of the geometric-hydraulic parameters for MBBR system designs for as-wide as practicable conditions is applicable in practice and enables for minimum delay time during start-up periods.

3.7 Cost Analysis – Conventional Systems vs. the Present Study

One of the main hurdles to the successful application of MBBRs in wastewater treatment is the long start-up period, which results in higher operational costs, late commissioning and the need for higher chemical and energy consumption for seeding and stabilization. Conventional MBBR systems, especially those featuring the common conventional cylindrical or chip-shaped media, often need 45–90 days at least for a stabilized biofilm, for example, when the real municipal wastewater to be treated. In contrast, shorter start-up times were observed in the current study where biofilm maturation was attained within 35–45 days depending on the medium used. In order to attempt to put an economic value on this advancement, a comparison cost-benefit was made based on major cost elements including sludge seeding requirements, aeration cost, chemicals to stabilize the process, labor and being able to avoid not using the capacity that would be provided by the full-size ARU. The values were adopted from available literature and scaled for a 1 MLD capacity (Falletti et al., 2014; Dereli et al., 2021; Ødegaard 2006; Zhu et al., 2015).

Table 3: Comparative Cost Analysis of Conventional vs. Optimized Start-Up Strategy (1 MLD Scale)

Cost Component	Conventional MBBR Start-up (60–90 days)	Present Study (35–45 days)	% Savings
Start-up Duration	60–90 days	35–45 days	40–50%
Seeding Sludge Volume (m^3)	80–100	50–60	30–40%
Energy for Aeration (kWh/day)	300–350	250–280	~15%
Process Chemicals (e.g., nutrients, buffers)	₹70,000–90,000	₹40,000–50,000	~40%
Labor & Monitoring (₹/day × duration)	₹2,500 × 75 = ₹1,87,500	₹2,500 × 40 = ₹1,00,000	~47%
Delayed Revenue from Treated Water	High (late commissioning)	Reduced (earlier commissioning)	N/A
Total Estimated Start-up Cost (₹)	₹3.8–4.5 Lakhs	₹2.2–2.5 Lakhs	~40% saving

These values indicate that the efficient media choice and operational aspect followed in this work could save significant expenses, which is estimated to be in the range of ₹1.5–2.0 lakhs for a standard 1 MLD plant for the start-up process only. Reduction of required sludge not only reduces transportation and disposal costs, but also decreases end-of-pipe sludge management needs. In addition, beginning operations in a shorter time period, allows the plant to start up more quickly, so that return on investment is more rapid and environmental compliance achieved. Furthermore, enhanced hydraulic efficiency, combined with a decreased biofilm formation rate, can decrease the need for external bioaugmentation and / or chemical stabilization agents applied in full scale flat sheet membrane-based STWs. These findings are consistent with the observations of emphasized that improved media design may help to minimize the aeration energy and chemicals added during start-up of MBBR by up to 30% (Vikrant et al., 2019). In summary, this study provides a technically and economically viable alternative to the traditional implementation of an MBBR by reducing the time, energy, and resources needed to establish a stable biofilm. This makes the method an economically attractive option to utilities and treatment plants managers when capital and operating budgets are limited.

4. Conclusions

This work investigated the effects of carrier media physical properties on the start-up and biofilm formation of a pilot-scale operation of a moving attached growth system treating actual municipal wastewater. The reactor was divided in a series of anaerobic, anoxic and aerobic compartments with the internal recirculation, as in this way a biological nutrient removal was reproduced. Four distinct packing materials were examined: dimensions, material density, surface area, voidage, and their influence on biofilm formation kinetics, pollutant removal efficiencies, and operational stability during the start-up period. Among the tested media, Media 2—a cylindrical polypropylene carrier with dimensions 12 mm × 25 mm and a protected surface area of 350 m^2/m^3—showed the most favorable performance. It achieved a maximum biofilm accumulation of 10.12 g TS/m² with a growth rate of 10.12 g TS/m²/day, reaching stabilization within 35 to 40 days. Media 3 and Media 4 exhibited slightly lower performance with stabilized biomass values of 8.51 g TS/m² and 6.16 g TS/m², respectively. Media 1, despite having the highest surface area (5500 m^2/m^3), demonstrated the poorest biofilm development, stabilizing at only 1.10 g TS/m² after 45 days, highlighting that excessively high surface area does not necessarily translate to improved performance, especially when accompanied by suboptimal hydrodynamic behavior. Pollutant removal efficiencies corresponded closely with biofilm growth trends. COD and BOD_5 concentrations in the effluent were consistently reduced to within 18–20 mg/L and 4–7 mg/L, respectively, across all trials. These values indicate the effective treatment potential of the system under real wastewater conditions. Additionally, ammonia removal improved in proportion to biofilm maturity, aligning with earlier observations that ammoniacal nitrogen reduction is strongly dependent on the establishment of nitrifying biofilms. The study demonstrated that traditional carrier selection criteria based solely on protected surface area are inadequate to predict biofilm performance. Instead, it proposed a new composite parameter—expressed as (Di × Voi) / HE, incorporating media diameter, voidage, and hydraulic efficiency—that better correlates with start-up time and biomass retention. This novel approach bridges the gap between mechanical carrier design and biological performance and offers a more comprehensive basis for selecting media in future MBBR applications. Economically, the shortened start-up time observed in this study offers a practical advantage. Compared to conventional MBBR systems that typically require 60 to 90 days for stabilization, the optimized configuration achieved steady-state biofilm within 35 to 45 days. The associated reduction in start-up sludge volume, aeration energy, chemical requirements, and labor contributed to an estimated savings of ₹1.5–2.0 lakhs for a 1 MLD plant, with significant potential for cost reduction at larger scales. The economic advantage, combined with enhanced treatment reliability, positions the findings of this study as highly relevant for utility managers and plant designers seeking efficient and cost-effective commissioning strategies. The novelty of this work lies in its integration of real wastewater testing, comprehensive media comparison, and the introduction of a geometric-hydraulic performance index for evaluating carrier effectiveness. Unlike earlier studies that rely on synthetic wastewater and laboratory reactors, this study demonstrates the operational feasibility of accelerating start-up in field-representative environments. Furthermore, it advances the understanding of how media design influences not only microbial adhesion and growth but also overall system performance and economics. These contributions make the research highly applicable for optimizing both new installations and the retrofitting of existing wastewater treatment facilities using moving attached growth technologies.

Declarations

Ethics Approval And Consent To Participate

Not applicable

Consent For Publication

Not applicable

Availability Of Data And Materials

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Competing Interests

"The authors declare that they have no competing interests" in this section.

Funding

No funding provided for this research.

Author's Contributions

Manish Kumar: Writing-original Draft; Conceptualization, Methodology.

Dayanand Sharma: Writing-review & editing; Supervision; Visualization.

Acknowledgement

Not Applicable

References

Alitaleshi, F., Daghbandan, A., and Pendashteh, A., 2024. Performance of rice husk biocarrier on ammonia nitrogen removal in the MBBR treating aquaculture wastewater using biological attached growth process: Performance and kinetic study. Journal of Environmental Chemical Engineering, 12, 111446. https://doi.org/10.1016/j.jece.2023.111446

Bassin, J. P., Dias, I. N., Cao, S. M. S., et al., 2016. Effect of increasing organic loading rates on the performance of moving-bed biofilm reactors filled with different support media: Assessing the activity of suspended and attached biomass fractions. Process Safety and Environmental Protection, 100, Pp. 131–141. https://doi.org/10.1016/j.psep.2016.01.007

Dereli, R. K., Clifford, E., and Casey, E., 2021. Co-treatment of leachate in municipal wastewater treatment plants: Critical issues and emerging technologies. Critical Reviews in Environmental Science and Technology, 51, Pp. 1079–1128. https://doi.org/10.1080/10643389.2020.1745014

Di Trapani, D., Mannina, G., Torregrossa, M., and Viviani, G., 2008. Hybrid moving bed biofilm reactors: A pilot plant experiment. Water Science and Technology, 57, Pp. 1539–1545. https://doi.org/10.2166/wst.2008.219

Dias, J., Bellingham, M., Hassan, J., et al., 2018. Impact of carrier media on oxygen transfer and wastewater hydrodynamics on a moving attached growth system. Chemical Engineering Journal, 351, Pp. 399–408. https://doi.org/10.1016/j.cej.2018.06.028

Falletti, L., Conte, L., and Maestri, A., 2014. Upgrading of a wastewater treatment plant with a hybrid moving bed biofilm reactor (MBBR). AIMS Environmental Science, 1, Pp. 45–52. https://doi.org/10.3934/environsci.2014.2.45

Gupta, A. K., Uddameri, V., Majumder, A., and Nimbhorkar, S. K., 2023. Wastewater engineering: Issues, trends, and solutions. CRC Press.

Gzar, H. A., Al-Rekabi, W. S., and Shuhaieb, Z. K., 2021. Application of moving bed biofilm reactor (MBBR) for treatment of industrial wastewater: A mini review. Journal of Physics: Conference Series. https://doi.org/10.1088/1742-6596/ (add volume and article number if available)

Jagaba, A. H., Abdulazeez, I., Lawal, D. U., et al., 2024. A review on the application of biochar as an innovative and sustainable biocarrier material in moving bed biofilm reactors for dye removal from environmental matrices. Environmental Geochemistry and Health, 46. https://doi.org/10.1007/s10653-023-01895-1

Madan, S., Madan, R., and Hussain, A., 2022. Advancement in biological wastewater treatment using hybrid moving bed biofilm reactor (MBBR): A review. Applied Water Science, 12, 141. https://doi.org/10.1007/s13201-022-01653-w

McQuarrie, J. P., and Boltz, J. P., 2011. Moving bed biofilm reactor technology: Process applications, design, and performance. Water Environment Research, 83, Pp. 560–575. https://doi.org/10.2175/106143010X12851009156286

Ødegaard, H., 2006. Innovations in wastewater treatment: The moving bed biofilm process. Water Science and Technology, 53, Pp. 17–33. https://doi.org/10.2166/wst.2006.284

Prasad, R., Sharma, D., Pandey, A. K., et al., 2024. Effect of plant density and hydraulic retention time on phytoremediation of greywater using water hyacinth and validation of its optimized result using artificial neural network. Canadian Journal of Chemical Engineering, 102, Pp. 113–128. https://doi.org/10.1002/cjce.25027

Prasad, R., Sharma, D., Yadav, K. D., and Ibrahim, H., 2023. Sustainable ternary treatment system for greywater and potential reuse. Canadian Journal of Chemical Engineering, 101, Pp. 1298–1309. https://doi.org/10.1002/cjce.24521

Prasad, R., Sharma, D., Yadav, K. D., and Ibrahim, H., 2021. Preliminary study on greywater treatment using water hyacinth. Applied Water Science, 11, 88. https://doi.org/10.1007/s13201-021-01422-4

Regmi, P., Thomas, W., Schafran, G., et al., 2011. Nitrogen removal assessment through nitrification rates and media biofilm accumulation in an IFAS process demonstration study. Water Research, 45, Pp. 6699–6708. https://doi.org/10.1016/j.watres.2011.10.009

Sharma, D., Saadi, I., Oazana, S., et al., 2024. Distribution of residence time in rotary-drum composting and implications for hygienization. Waste Management, 179, Pp. 22–31. https://doi.org/10.1016/j.wasman.2024.02.047

Wang, J. H., Zhao, X. L., Hu, Q., et al., 2022. Effects mechanism of bio-carrier filling rate on rotating biofilms and the reactor performance optimization method. Chemosphere, 308, 136176. https://doi.org/10.1016/j.chemosphere.2022.136176

Xu, J., Lai, Z., Zhang, W., et al., 2025. Moving bed biofilm reactor for blackwater treatment: Insights into pollutant removal, microbial communities, and water quality prediction through machine learning. Frontiers of Environmental Science and Engineering, 19. https://doi.org/10.1007/s11783-025-2022-7

Zhu, Y., Zhang, Y., Ren, H. Q., et al., 2015. Physicochemical characteristics and microbial community evolution of biofilms during the start-up period in a moving bed biofilm reactor. Bioresource Technology, 180, Pp. 345–351. https://doi.org/10.1016/j.biortech.2015.01.006

Zhuang, Y., Zhang, Z., Zhou, Z., et al., 2019. Co-treatment of shale-gas produced water and municipal wastewater: Removal of nitrogen in a moving-bed biofilm reactor. Process Safety and Environmental Protection, 126, Pp. 269–277. https://doi.org/10.1016/j.psep.2019.04.010

F., Farooqi, I.H., 2023. Efficacy of electrocoagulation treatment for the abatement of heavy metals: an overview of critical processing factors, kinetic models and cost analysis. Sustainability 15(2), 1708. https://doi.org/10.3390/su15021708.

Licht, K., Posavčić, H., Halkijević, I., Markić, M., Zlomislić, J., 2022. The influence of the initial concentration of heavy metals and the electrode material on the efficiency of electrocoagulation water treatment. Available at: https://primeus.grad.hr/wp-content/uploads/2023/01/03-Licht-The-influence.pdf

Merzouk, B., Gourich, B., Sekki, A., Madani, K., Chibane, M., 2009. Removal of turbidity and separation of heavy metals using electrocoagulation–electroflotation technique. J. Hazard. Mater.

164(1), Pp. 215–222. https://doi.org/10.1016/j.jhazmat.2008.07.144.

Parga Torres, J.R., 2024. Pollutants removal and electrocoagulation processes for high quality precipitate from cyanide-contaminated solutions. Asp. Min. Miner. Sci. 12(5). https://doi.org/10.31031/amms.2024.12.000799.

Peng, C., Liu, Y., Bi, J., Xu, H., Ahmed, A.-S., 2011. Recovery of copper and water from copper-electroplating wastewater by the combination process of electrolysis and electrodialysis. J. Hazard. Mater. 189(3), Pp. 814–820. https://doi.org/10.1016/j.jhazmat.2011.03.034.

Perrelli, M., Wu, R., Liu, D.J., Lucchini, R.G., Del Bosque-Plata, L., Vergare, M., Gragnoli, C., 2022. Heavy metals as risk factors for human diseases – a Bayesian network approach. https://doi.org/10.26355/eurrev_202212_30681.

Phu, T.K.C., Nguyen, P.L., Phung, T.V.B., 2025. Recent progress in highly effective electrocoagulation-coupled systems for advanced wastewater treatment. iScience 28(3), 111965. https://doi.org/10.1016/j.isci.2025.111965.

Shaker, O.A., Matta, M.E., Safwat, S.M., 2021. Nickel and chromium removal by electrocoagulation using copper electrodes. Desalin. Water Treat. 213, Pp. 371–380. https://doi.org/10.5004/dwt.2021.26722.

Un, U.T., Ocal, S.E., 2015. Removal of heavy metals (Cd, Cu, Ni) by electrocoagulation. Int. J. Environ. Sci. Dev. 6(6), Pp. 425–429. https://doi.org/10.7763/ijesd.2015.v6.630.

World Health Organization, 2021. Compendium of WHO and other UN guidance on health and environment. World Health Organization