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Original Article

Enhancing Wastewater Treatment Efficiency Using MBBR: A Media Selection Approach

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Abstract
Background: Wastewater treatment is a critical environmental challenge, and moving bed biofilm reactor (MBBR) technology is an effective solution. The selection of appropriate biofilm media significantly impacts treatment efficiency, particularly in terms of organic matter and nutrient removal. This study aims to optimize media selection for MBBR systems to improve wastewater treatment.
Methods: Three biofilm media types-K3, MB3, and K5-were evaluated based on key properties such as specific surface area (SSA), porosity, buoyancy, and economic feasibility. The analytical hierarchy process (AHP) was employed to assess and prioritize these criteria. Expert Choice software facilitated the analysis, followed by a laboratory-scale investigation to assess pollutant removal efficiency.
Results: K5 media outperformed K3 and MB3 in terms of nitrogen removal (90%), chemical oxygen demand (COD) reduction (90%), biochemical oxygen demand (BOD) elimination (95%), and TSS removal (89%). K5 also demonstrated superior efficiency in pollutant removal while maintaining consistent pH regulation. K3 and MB3 displayed relatively lower performance, especially in nitrogen and COD removal.
Conclusion: The study confirms that K5 media, selected using the AHP method, provides the highest treatment efficiency in MBBR systems. The AHP-based media selection process enhances the decision-making process, ensuring that economic and performance factors are adequately considered. Future studies should focus on scaling up the MBBR system with K5 media to further evaluate its long-term performance in real-world conditions.
Keywords: Wastewater, Media, Pollution, Hierarchical analysis, Environment

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Introduction
The moving bed biofilm reactor (MBBR) technology revolutionizes wastewater treatment by combining the efficiency of activated sludge processes with biological filters, optimizing space utilization compactly. Unlike conventional biological reactors, which struggle with sedimentation and sludge management, MBBR overcomes these challenges while maintaining high efficiency. Notably, it benefits from removing organic matter, phosphorus, and nitrogen from wastewater.[1,2]

Technologies for producing clean water and energy have garnered global attention owing to water scarcity, resource depletion, and global warming. Municipal wastewater, the most abundant type of wastewater, falls into the category of low-strength waste streams characterized by low organic strength and high particulate organic matter content.[3-9] Various treatment technologies are employed to treat wastewater effectively, ensuring it is contaminant-free before release into the environment. Proficiency in this field enables proper treatment approaches for different wastewater types, including domestic and industrial sources. These methods encompass physical and biological techniques, ensuring comprehensive treatment and environmental safety.[10-12]

In water treatment technologies, a range of physical, chemical, and biological methods exist. While physical and chemical methods are cost-effective because of their simplicity, biological methods have emerged as optimal choices owing to their inherent simplicity, efficiency, and eco-compatibility.[13] Biological methodologies are categorized into aerobic and anaerobic systems. Examples like the activated sludge process, membrane bioreactor, and upflow anaerobic sludge blanket represent aerobic systems. However, challenges persist, notably the need to regularly clean membranes in membrane bioreactor setups.[14] The MBBR is an innovative and cost-effective approach to water treatment. Studies have explored its efficacy by comparing different biofilm media or examining the impact of carrier shape and surface properties on efficiency. These investigations provide insights into optimizing MBBR performance through carrier selection and design considerations.[15] In the MBBR process, microorganisms form biofilms on various surfaces, exhibiting greater resilience under diverse wastewater treatment conditions and enhancing efficiency compared to conventional methods. The dynamism and buoyancy of carriers play crucial roles: reduced media weight promotes movement, aiding biofilm detachment and biomass control, while smaller-diameter media provide a larger specific surface area (SSA), enhancing biofilm growth. Conversely, larger media diameters reduce density and sedimentation speed, impacting overall efficiency.[16] Figure S1 displays various types of media used in the process.[17]

In a study by Chu and Wang, a comparative analysis of biofilm media, such as iodegradable polymer polycaprolactone (PCL) and degradable polyurethane foams (PUFs), revealed that the PCL carrier was more effective for removing total nitrogen (TN) because of its lower carbon to nitrogen (C/N) ratio.[18] Researchers also examined filtration media like zeolite, sand, and volcanic rock in up-flow constructed wetland combined with microbial fuel cell (UCW-MFC) systems for wastewater treatment and bioelectricity generation. Zeolite outperformed other media due to its larger SSA, distinctive framework structure, and porous composition, effectively removing pollutants such as chemical oxygen demand (COD), NH_4^+, nitrate (NO_3^-), and total phosphorus (TP).[19] Moreover, studies have focused on the preference for the AnoxKaldnes K3 carrier over the Mutag BioChip due to its superior COD removal efficiency. The introduction of innovative sponge biomedia in MBBR systems has been shown to increase microbial diversity and enhance nitrification performance.[20] However, literature exploring these specific advancements remains comparatively limited.[21] When selecting optimal biofilter media, critical parameters include SSA, porosity, clogging potential, toxicity, void ratio, dynamics, density, surface roughness, and passage diameter. Emphasizing high SSA and reduced clogging is paramount in carrier design. Although numerous studies aim to optimize biological carrier designs, clogging during operation often significantly diminishes treatment efficiency.[22] Materials such as polypropylene, polycarbonate, ABS, polyamide, and polyethylene are commonly used in biofilm media production.[23] Zhu et al stated that thermoplastic polymers like polyethylene, polypropylene, and polystyrene exhibit excellent mechanical, physical, and chemical properties, making them highly suitable for biofilm carriers.[24] In Elliott and colleagues' study, clogging concerns were addressed, concluding that a minimum passage diameter of 1500 μm is necessary. For cylindrical media, a minimum diameter of 2.5 mm is recommended to mitigate clogging, with mathematical models developed for designing MB3 and K3 Kaldnes media.[25]

While biofilter design research exists, there is a notable gap in comparative analyses of various media types. The objective of the current research was to enhance wastewater treatment efficiency in the MBBR method by identifying the most optimal media among three proposed options. How does the performance of New Media K5 compare to other media types? This study evaluated also established properties of wastewater treatment media specific to the site, aiming to optimize the treatment process.

Materials and Methods

The primary objective of this research was to identify the most effective medium for treating domestic wastewater by evaluating key parameters, including COD, total suspended solids (TSS), and pH, on a laboratory scale. To determine the optimal choice among the three proposed media types (K3, MB3, and K5), three experts specializing in water pretreatment technology assessed the criteria using the analytical hierarchy process (AHP) method. Expert Choice software was employed to analyze and rank the media based on these criteria. Following the AHP analysis, a laboratory-scale investigation was conducted to assess the performance of the selected medium in domestic wastewater treatment. The study compared the chosen medium with the other two media types, focusing on parameters such as TN, TP, COD, TSS, and pH to evaluate its effectiveness.

Analytic Hierarchy Process

The AHP is a critical decision-making tool designed to address complex problems with a hierarchical structure. This method integrates criteria, sub-criteria, and alternatives to systematically determine the best option.[26] The process begins with defining the relative importance of the criteria through pairwise comparisons, which then guide the evaluation of alternatives against these criteria. AHP consists of four main stages: formulating a hierarchical model, performing pairwise evaluations, assessing alternatives, and synthesizing results. This approach combines mathematical precision with human judgment, enabling a detailed analysis of diverse factors and facilitating effective decision-making.

In this study, selecting the most suitable medium was particularly challenging due to the many influencing factors. Assigning appropriate weights to these criteria added complexity and uncertainty to the decision-making process.[27] Consequently, three experts provided their insights through a structured questionnaire to determine the evaluation criteria. A subjective approach, involving a paired comparison matrix and a 9-point scale for quantifying preferences, was employed. Expert Choice software was used to calculate weights, perform pairwise comparisons, and assess compatibility rates, as demonstrated in Table S1.[28]

Review the Criteria for the Preferred Media

When evaluating the various polymeric media available in the market today, it is essential to consider their shapes, sizes, and performance attributes. One of the primary criteria is the carrier medium's void ratio, defined as the ratio of void volume to the solid biofilter volume. Among the options analyzed, K3, MB3, and K5 demonstrate favorable void ratios of 66.39%, 67.14%, and 69.42%, respectively.[29] Another crucial parameter is the SSA, which directly influences the media's capacity to support bacterial growth and enhance filtration efficiency. The SSAs for K3, MB3, and K5 are 500 m^2/m^3, 1200 m^2/m^3, and 1600 m^2/m^3, respectively. These attributes underline the superior performance potential of these media options in wastewater treatment applications.

MB3

The WaterTek MB3 Movable Bed Filter is a highly efficient medium specifically designed for moving bed filter systems. Constructed with a corrugated cylindrical structure made from durable polyethylene, MB3 creates an optimal environment for bacterial growth. With a SSA of 1200 m^2/m^3, this medium provides sufficient space for effective filtration processes. The cross-sectional design of the MB3 carrier is illustrated in Figure S2.[29]

K3

The K3 media is a preferred choice due to its resemblance to the K1 media in shape, but with a larger diameter and extended fins (Figure S3). Precisely engineered, it offers an impressive SSA of approximately 3800 m^2/m^3. The AnoxKaldnes K3, a type of suspended media, is widely regarded as a benchmark in wastewater treatment due to its extensive adoption and rigorous testing in system design. One of the standout features of the K3 media is its 25% increase in specially protected surface area compared to its predecessor, significantly enhancing its performance in biofilm formation and filtration. Additionally, the design cost of this carrier is considerably lower than other media analyzed in this research, further solidifying its position as a cost-effective and high-performing option for wastewater treatment applications.

AnoxKaldnes K5

The AnoxKaldnes K5 media is a specialized variant explicitly engineered for nitrogen removal in wastewater treatment. Although it shares a similar shape to the K1 media, the K5 is made from a distinct plastic material, which provides a significantly higher surface area that promotes the attachment and growth of nitrifying bacteria. With an impressive SSA of 1600 m^2/m^3, this medium is highly effective in supporting the biofilm formation necessary for efficient nitrogen removal. As the latest generation of suspended media, the K5 introduces an innovative design with a specially protected surface and a complex internal structure featuring 64 internal media networks (Figure S4).[30] This intricate internal geometry, achieved through advanced extrusion molding and part design, significantly enhances the media's performance. Additionally, the abundant internal surfaces, combined with the flower-like shape of the external cross-section, improve the mechanical strength and durability of the carrier. These features ensure the K5 media maintains its structural integrity throughout its operational lifespan, preventing deformation or breakage.

Within the MBBR method, the dimensions and configurations of the media significantly impact both performance and overall costs. Precisely tailoring the media is crucial for ensuring efficient nutrient and oxygen transfer.[23] Figure 1 illustrates the AHP method, highlighting the relationship between the criteria and options considered in this study.

Results and Discussion

This study aimed to identify and select the most suitable media for evaluation and comparison against control media using the AHP method. Suspended media, integral to the latest advancements in wastewater treatment processes utilizing attached growth, plays a critical role in cultivating digestive bacteria within the biological segment of the treatment process. Its inclusion significantly reduces the aeration tank volume required for wastewater treatment, thereby lowering associated costs while improving the quality of discharged effluent. Additionally, this approach eliminates the need for

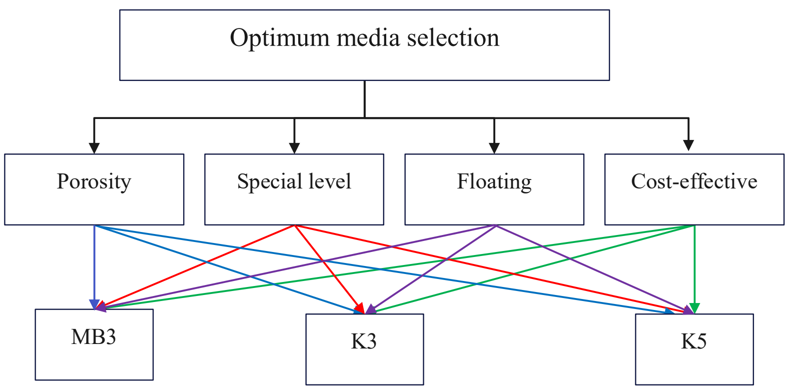

Figure 1. AHP Scheme for Optimal Media Selection

highly skilled operators, minimizes sludge production, and enhances the system's resilience against organic and hydraulic shocks.[31] To facilitate the selection process, criteria such as porosity, cost-effectiveness, SSA, and buoyancy were weighted based on evaluations provided by three wastewater treatment experts. A matrix was subsequently constructed, and the Expert Choice software was utilized to determine the relative weights of both the criteria and the options. The results are illustrated in Figure 2.

In Figure 3, the final result from the Expert Choice software highlights the K5 media as the top-performing option, attributed to the higher weight assigned to its criteria. The inconsistency rate, calculated at 0.07 (overall inconsistency = 0.07), is notable as it falls below the acceptable threshold of 0.1, confirming the compatibility and reliability of the comparison matrix. Figure 4 illustrates the sensitivity analysis, a valuable tool for exploring the range of possible outcomes centered around a target. This method is particularly critical

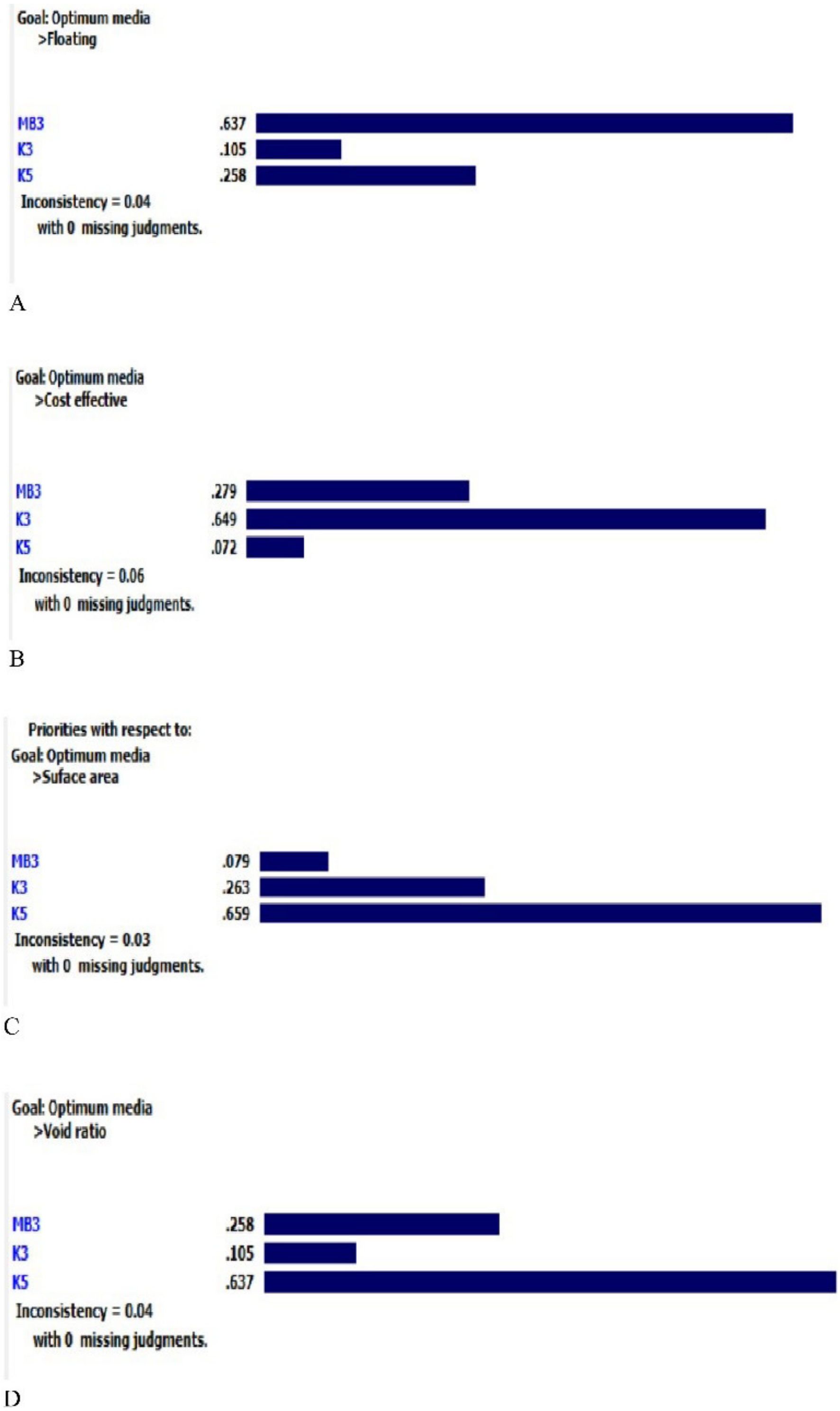

Figure 2. (A) Prioritization of options according to the buoyancy criterion, (B) Prioritization of options according to the economic criteria, (C) Prioritization of options relative to the special level criterion, (D) Prioritizing the options according to the porosity criterion

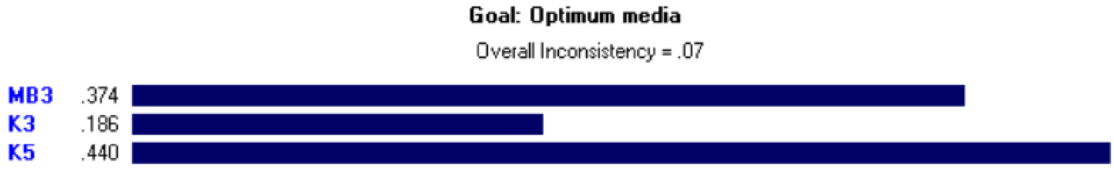

Figure 3. Choosing the Best Option with Respect to the Overall Goal

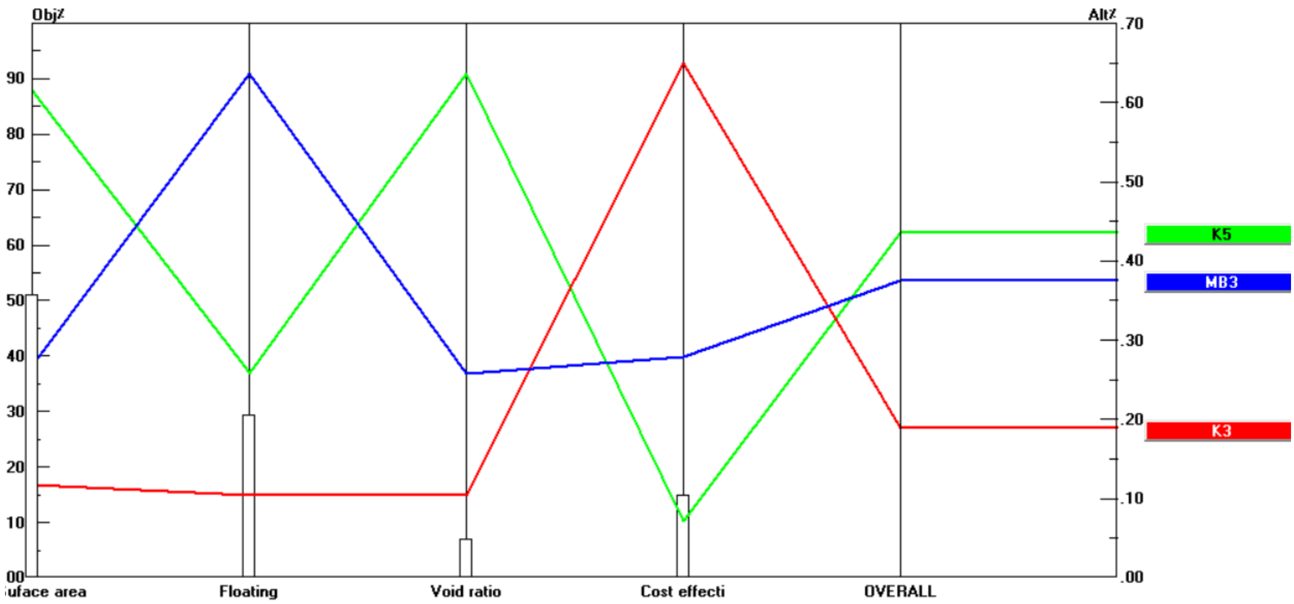

Figure 4. Sensitivity Analysis Chart

in scenarios where uncertainty exists regarding key variables. Sensitivity analysis examines how variations in input factors influence the output, providing a deeper understanding of their significance and impact within the decision-making framework.

To evaluate the performance of the selected media compared to alternative options, a biofilm reactor utilizing a moving bed was constructed. As shown in Figure S5, the reactor tank dimensions are 25 × 25 × 45 cm. During the research period, daily measurements were taken while varying the input flow to the pilot setup to assess efficiency under different conditions. Notably, due to the sealed nature of the sewage treatment system for housing applications, the organic load assessment was based on domestic sewage.

The solids retention time (SRT), which represents the average time sludge remains in the system, typically ranges from 3 to 5 days depending on the temperature of the mixed liquid. In this study, the SRT value was maintained at approximately 3 days. Hydraulic retention time (HRT) data varied across different stages: 3 hours for balance and primary sedimentation, 2 hours for flocculation, about 1 hour for COD levels ranging between 300 and 600 mg/L, 5 to 7 hours for aeration, and 3 to 4 hours for secondary sedimentation. Throughout the research, key input and output parameters-including pH, COD, BOD, TSS, nitrogen, and phosphorus-were measured and documented (Table 1). TN in wastewater encompasses all forms of nitrogen, including organic nitrogen, ammonia (NH_3), NO_3^-, and nitrite (NO_2^-). Monitoring TN levels is essential in wastewater treatment, as excessive nitrogen discharge into water bodies can lead to eutrophication. This phenomenon, characterized by algal blooms, oxygen depletion, and harm to aquatic life, poses significant environmental challenges. Controlling and reducing TN is a critical aspect of regulatory compliance and wastewater treatment processes.[32] TP in wastewater reflects the concentration of phosphorus compounds present. Elevated TP levels can also harm aquatic ecosystems by promoting algal blooms. Treatment methods for phosphorus removal include chemical precipitation, biological removal, adsorption, and advanced technologies such as membrane filtration. These approaches aim to maintain safe phosphorus levels and protect water ecosystems. Regular monitoring ensures adherence to environmental standards.[33]

Table 1. Characteristics of Incoming and Outgoing Sewage

Measured Parameters	Incoming Wastewater	Outgoing Wastewater			
		Without Media	K5	K3	MB3
pH	6.6	No change	7-7.5	7-7.5	7-7.5
COD (mg/L)	300-600	180	30	45	60
BOD (mg/L)	150-300	90	7.5	30	37.5
TSS (mg/L)	150-400	105	16.5	45	30
TN (mg/L)	15-60	No change	1.5	3	4.5
TP (mg/L)	5-15	No change	2.5	2.5	2.5

The K5 media demonstrates slightly superior removal efficiency across various pollutants, including nitrogen, COD, BOD, and TSS, compared to K3 and MB3 media. Table 2 provides a detailed analysis of the performance of K3, K5, and MB3 media in terms of pollutant removal efficiency and pH adjustment. The K5 carrier exhibits the highest nitrogen removal efficiency at 90%, outperforming K3, which achieves 80%, and MB3, which demonstrates a lower efficiency of 70%. Phosphorus removal efficiency remains consistent across all three media, ranging from 50 to 60%, with no significant differences observed. The K5 carrier achieves the highest COD removal efficiency at 95%, followed by K3 at 85%, and MB3 at 80%. In line with COD removal trends, the K5 carrier also excels in BOD removal, achieving an efficiency of 95%. The K3 media demonstrates a range of 75 to 85%, while MB3 shows a slightly lower range of 70 to 80%. The K5 media offers exceptional performance in reducing Total Suspended Solids (TSS), with an efficiency of 89%. By comparison, K3 and MB3 media demonstrate efficiencies ranging from 60 to 70%. All three media exhibit consistent performance in pH adjustment, with minimal differences observed among them.

In the MBBR process, maximizing wastewater-treating microorganisms relies on the use of floating media within the aeration tank. The efficiency of MBBR systems is largely determined by the biofilm media, with the specific or effective surface area of the media playing a critical role in supporting biofilm development. The findings highlight that the effective removal of organic matter in the moving bed process depends primarily on the available surface area for biomass growth. While carrier size and shape may influence this area, maintaining a consistent SSA across different media minimizes performance discrepancies. Therefore, process design should prioritize pollutant removal rates per unit area as a key guiding principle.[34] Table 1 presents measurements of pH, COD, and TSS in incoming wastewater. Post-treatment evaluations reveal that the K5 media achieved remarkable COD removal efficiency at an 8-hour HRT, reaching 90%. This study further benchmarks K5 media against four others. A comparison between K5 media's COD removal efficiency (90%) and that of K3 media (80%) and MB3 media (84%) reported in previous studies confirms the superior performance of K5 in this study. In terms of TSS removal, K5 media outperformed K3 media, which achieved 79% efficiency in other studies. The findings of Ahmadlouydarab and Mahna[17] validate K5's exceptional TSS removal capability, with a rate of 89%. This superior performance is attributed to K5's elevated SSA, which enhances microorganism attachment and growth, facilitating robust biofilm formation and effective pollutant removal.

Table 2. Comparison of Three Media in Removing Pollutants

Pollutant	Efficiency (%) K5	Efficiency (%) K3	Efficiency (%) MB3
TN (mg/L)	90	80	70
TP (mg/L)	50-60	50-60	50-60
COD (mg/L)	90	85	80
BOD (mg/L)	95	75-85	70-80
TSS (mg/L)	89	70	80
pH	Comparable	Comparable	Comparable

Conclusion

This study demonstrates the effectiveness of the AHP in selecting optimal media for enhancing wastewater treatment in MBBR systems. Among the three media evaluated-K3, MB3, and K5-K5 emerged as the most efficient, achieving superior removal rates for nitrogen (90%), COD (90%), BOD (95%), and TSS (89%), while maintaining comparable performance for phosphorus removal and pH regulation. The findings underscore the pivotal role of media-specific attributes, such as porosity, SSA, buoyancy, and cost-effectiveness, in optimizing MBBR performance. The use of AHP provided a structured, data-driven framework that integrated technical and economic considerations to support informed decision-making. The research emphasizes the requirement for further studies to explore the scalability of K5 media in full-scale applications and its performance under varying operational conditions. Future investigations could also focus on integrating advanced materials or hybrid technologies to further improve pollutant removal efficiency and reduce operational costs. By combining rigorous carrier selection methodologies with innovative biofilm media designs, this study contributes to the development of sustainable and efficient wastewater treatment systems, addressing global environmental and public health challenges.

Authors' Contribution

Conceptualization: Mehdi Shamsabadizadeh, Nasser Mehrdadi, Akbar Baghvand.
Data curation: Mehdi Shamsabadizadeh, Nasser Mehrdadi, Akbar Baghvand.
Formal analysis: Mehdi Shamsabadizadeh.
Investigation: Mehdi Shamsabadizadeh.
Methodology: Mehdi Shamsabadizadeh, Nasser Mehrdadi.
Project administration: Nasser Mehrdadi, Akbar Baghvand.
Software: Mehdi Shamsabadizadeh.
Supervision: Nasser Mehrdadi.
Validation: Mehdi Shamsabadizadeh, Nasser Mehrdadi, Akbar Baghvand.
Visualization: Mehdi Shamsabadizadeh, Nasser Mehrdadi.
Writing-original draft: Mehdi Shamsabadizadeh.
Writing-review & editing: Mehdi Shamsabadizadeh, Nasser Mehrdadi.

Competing Interests

The authors declare that they have no financial or personal relationships with any individuals or organizations that could inappropriately influence or bias the content of this paper. This includes, but is not limited to, employment, consultancies, honoraria, grants, stock ownership, or any other forms of financial or personal connections.

Ethical Approval

This research was conducted in accordance with ethical guidelines, and no specific ethical considerations were applicable to this study.

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Supplementary Files
Supplementary file 1 contains Table S1 and figures S1-S5.

References
1. Sohail N, Ahmed S, Chung S, Nawaz MS. Performance comparison of three different reactors (MBBR, MBR and MBBMR) for municipal wastewater treatment. Desalin Water Treat. 2020;174:71-8. doi: 10.5004/dwt.2020.24866.
2. Shokri R, Jalilzadeh Yengejeh R, Babaei AA, Derikvand E, Almasi A. Removal of azithromycin from wastewater using advanced oxidation processes (UV/H2O2) and moving-bed biofilm reactor (MBBR) by the response surface methodology (RSM). J Adv Environ Health Res. 2019;7(4):249-59. doi: 10.22102/jaehr.2019.205819.1146.
3. Ebadi M, Asareh A, Jalilzadeh Yengejeh R, Hedayat N. Investigation of electro-coagulation process for phosphate and nitrate removal from sugarcane wastewaters. Iran J Toxicol. 2021;15(1):19-26. doi: 10.32598/ijt.15.1.483.4.
4. Azarm L, Javadzadeh N, Jalilzadeh Yengejeh R. Investigation of *Chlorella vulgaris* capacity in absorption of nitrate and phosphate from wastewater of fish farming pool in Khuzestan province. J Anim Environ. 2020;12(2):291-8. doi: 10.22034/aej.2020.107264.
5. Nikpour B, Jalilzadeh Yengejeh R, Takdastan A, Hassani AH, Zazouli MA. Studying the effluent quality of enhanced modified Ludzack Ettinger-oxic settling anaerobic process (E-MLE-OSA) for treating real municipal wastewater. J Adv Environ Health Res. 2021;9(4):345-60. doi: 10.32598/jaehr.9.4.1243.
6. Shobirynia M, Jalilzadeh Yengejeh R, Derikvand E, Mohammadi Rouzbahani M. Comparison of electro-fenton and photoelectro-fenton for removal of acrylonitrile butadiene styrene (ABS) from petrochemical wastewater. Main Group Chem. 2023;23(2):133-44. doi: 10.3233/mgc-230063.
7. Mahdavi M, Mahvi AH, Salehi M, Sadani M, Biglari H, Tashauoei HR, et al. Wastewater reuse from hemodialysis section by combination of coagulation and ultrafiltration processes: case study in Saveh-Iran hospital. Desalin Water Treat. 2020;193:274-83. doi: 10.5004/dwt.2020.25799.
8. Verijkazemi K, Jalilzadeh Yengejeh R. Simulation of an industrial wastewater treatment plant by up-flow anaerobic fixed bed bioreactor based on an artificial neural network. Avicenna J Environ Health Eng. 2022;9(1):1-8. doi: 10.34172/ajehe.2022.01.
9. Heidari Farsani M, Jalilzadeh Yengejeh R, Hajiseyed Mirzahosseini A, Monavari M, Hassani AH, Mengelizadeh N. Study of the performance of bench-scale electro-membranes bioreactor in leachate treatment. Adv Environ Technol. 2021;7(3):209-20. doi: 10.22104/aet.2022.5266.1426.
10. Takdastan A, Kordestani B, Nisi A, Jalilzadeh Yangjeh R. Study of operational and maintenance problems and parameters of extended aeration activated sludge process in Golestan hospital wastewater treatment plant, Ahvaz, and their solutions. J Environ Health Eng. 2016;3(4):270-9. doi: 10.18869/acadpub.jehe.3.4.270.
11. Amini Fard F, Jalilzadeh Yengejeh R, Ghaeni M. Efficiency of microalgae *Scenedesmus* in the removal of nitrogen from municipal wastewaters. Iran J Toxicol. 2019;13(2):1-6. doi: 10.32598/ijt.13.2.483.2.
12. Azanaw A, Birlie B, Teshome B, Jemberie M. Textile effluent treatment methods and eco-friendly resolution of textile wastewater. Case Stud Chem Environ Eng. 2022;6:100230. doi: 10.1016/j.cscee.2022.100230.
13. Birniwa AH, Ali U, Kutty SR, Jagaba AH, Noor A. Innovative and eco-friendly technologies for the upgradation of pharmaceutical wastewater treatment processes. In: Khan AH, Khan NA, Naushad M, Aziz HA, eds. The Treatment of Pharmaceutical Wastewater. Elsevier; 2023. p. 367-98. doi: 10.1016/b978-0-323-99160-5.00006-0.
14. Grace Pavithra K, Jaikumar V, Kumar PS, Sundar Rajan P. A review on cleaner strategies for chromium industrial wastewater: present research and future perspective. J Clean Prod. 2019;228:580-93. doi: 10.1016/j.jclepro.2019.04.117.
15. Garcia KA, McLee P, Schuler AJ. Effects of media length on biofilms and nitrification in moving bed biofilm reactors. Biofilm. 2022;4:100091. doi: 10.1016/j.bioflm.2022.100091.
16. Kruszelnicka I, Kramarczyk DG, Poszwa P, Stręk T. Influence of MBBR carriers' geometry on its flow characteristics. Chem Eng Process Process Intensif. 2018;130:134-9. doi: 10.1016/j.cep.2018.06.009.
17. Ahmadlouydarab M, Mehrazaran M. Application of lab-scale MBBR to treat industrial wastewater using K3 carriers: effects of HRT, high COD influent, and temperature. Int J Environ Sci Nat Resour. 2019;20(2):35-42. doi: 10.19080/ijesnr.2019.20.556031.
18. Chu L, Wang J. Comparison of polyurethane foam and biodegradable polymer as carriers in moving bed biofilm reactor for treating wastewater with a low C/N ratio. Chemosphere. 2011;83(1):63-8. doi: 10.1016/j.chemosphere.2010.12.077.
19. Yakar A, Türe C, Türker OC, Vymazal J, Saz Ç. Impacts of various filtration media on wastewater treatment and bioelectric production in up-flow constructed wetland combined with microbial fuel cell (UCW-MFC). Ecol Eng. 2018;117:120-32. doi: 10.1016/j.ecoleng.2018.03.016.
20. Mazioti AA, Koutsokeras LE, Constantinides G, Vyrides I. Untapped potential of moving bed biofilm reactors with different biocarrier types for bilge water treatment: a laboratory-scale study. Water. 2021;13(13):1810. doi: 10.3390/w13131810.
21. Dezotti M, Lippel G, Bassin JP. Advanced Biological Processes for Wastewater Treatment. Springer; 2018.
22. Proano-Pena G, Carrano AL, Blersch DM. Analysis of very-high surface area 3D-printed media in a moving bed biofilm reactor for wastewater treatment. PLoS One. 2020;15(8):e0238386. doi: 10.1371/journal.pone.0238386.
23. Spoerk M, Holzer C, Gonzalez-Gutierrez J. Material extrusion-based additive manufacturing of polypropylene: a review on how to improve dimensional inaccuracy and warpage. J Appl Polym Sci. 2020;137(12):48545. doi: 10.1002/app.48545.
24. Zhu L, Yuan H, Shi Z, Deng L, Yu Z, Li Y, et al. Metagenomic insights into the effects of various biocarriers on moving bed biofilm reactors for municipal wastewater treatment. Sci Total Environ. 2022;813:151904. doi: 10.1016/j.scitotenv.2021.151904.
25. Elliott O, Gray S, McClay M, Nassief B, Nunnelley A, Vogt E, et al. Design and manufacturing of high surface area 3D-printed media for moving bed bioreactors for wastewater treatment. J Contemp Water Res Educ. 2017;160(1):144-56. doi: 10.1111/j.1936-704X.2017.03246.x.
26. Ho W, Ma X. The state-of-the-art integrations and applications of the analytic hierarchy process. Eur J Oper Res. 2018;267(2):399-414. doi: 10.1016/j.ejor.2017.09.007.
27. Larichev OI, Moshkovich HM. ZAPROS-LM—a method and system for ordering multiattribute alternatives. Eur J Oper Res. 1995;82(3):503-21. doi: 10.1016/0377-2217(93)e0143-l.
28. Saaty TL. The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. New York: McGraw-Hill; 1980..
29. Nyuysoni SB, Mutua JM, Home PG. Mathematical model development and 3D printing of cylindrically shaped biofilm carrier media from recycled plastic waste for wastewater treatment. J Environ Prot. 2022;13(1):15-31. doi: 10.4236/jep.2022.131002.

30. Boyle K. Optimization of Moving Bed Biofilm Reactor (MBBR) Operation for Brewery Wastewater Treatment [dissertation]. University of Ottawa; 2019. doi: 10.20381/ruor-23395.
31. Madan S, Madan R, Hussain A. Advancement in biological wastewater treatment using hybrid moving bed biofilm reactor (MBBR): a review. Appl Water Sci. 2022;12(6):141. doi: 10.1007/s13201-022-01662-y.
32. Phanwilai S, Kangwannarakul N, Noophan P, Kasahara T, Terada A, Munakata-Marr J, et al. Nitrogen removal efficiencies and microbial communities in full-scale IFAS and MBBR municipal wastewater treatment plants at high COD:N ratio. Front Environ Sci Eng. 2020;14(6):115. doi: 10.1007/s11783-020-1374-2.
33. Kängsepp P, Sjölin M, Mutlu AG, Teil B, Pellicer-Nàcher C. First full-scale combined MBBR, coagulation, flocculation, Discfilter plant with phosphorus removal in France. Water Pract Technol. 2020;15(1):19-27. doi: 10.2166/wpt.2019.081.
34. Proano-Pena G, Carrano AL, Blersch DM. Analysis of very-high surface area 3D-printed media in a moving bed biofilm reactor for wastewater treatment. PLoS One. 2020;15(8):e0238386. doi: 10.1371/journal.pone.0238386.