Vol. 23, No. 3(2024) IA24347
Revista Mexicana de Ingeniería Química
Ingeniería Ambiental

Municipal wastewater treatment in a hybrid biofiltration system packed with agave fiber

Tratamiento de aguas residuales municipales en un sistema híbrido de biofiltros empacados con fibra de agave

A. Serrano-Meza[1], J.M. Vigueras-Cortes[2]*, C.D. Allen[3]
[1]Tecnológico Nacional de México, Instituto Tecnológico del Valle del Guadiana, Carretera Durango-México km. 22.5, Villa Montemorelos, C.P. 34371, Durango, Dgo., México.
[2]Instituto Politécnico Nacional, CIIDIR-Durango, Calle Sigma N°119, Fracc. 20 de Noviembre II, C.P. 34220, Durango, Dgo., México.
[3]The University of the West Indies, Cave Hill Campus, Barbados.
Received: June 3, 2024; Accepted: August 19, 2024

Abstract

A hybrid biofiltration system (HBS) consisting of two biofilters, one anaerobic and the other aerobic, connected in series and packed with agave fiber, a byproduct of artisanal mezcal production, for treating municipal wastewater was evaluated. Five hydraulic loading rates (HLRs) of 0.27, 0.54, 0.80, 1.07, and 1.34 m^3/m^2d, were tested. The air supply rate was set at 0.62 m^3/m^2h. Initially, the time needed for microbial population conditioning on the filter material was determined. Subsequently, the other four HLRs were examined to determine the maximum treatment capacity of the HBS. Microbial conditioning was achieved after 64 days of operation with the HLR of 0.27 m^3/m^2d. The highest removal efficiency of BOD_5 was recorded at 94% (17± 5 mg/L) and COD at 88% (130 mg/L) with HLR of 0.54 m^3/m^2d. Throughout the study, the removal of TSS remained within standard levels, ranging from 89% (16 ± 8 mg/L) at HLR from 0.54 to 1.34 m^3/m^2d. Additionally, with HLR of 0.80 m^3/m^2d, a removal efficiency of fecal coliforms of 4 logarithmic units was achieved. In conclusion, a hybrid biofiltration system packed with organic material proves effective for treating wastewater in rural communities, meeting the concentration standards outlined in NOM-001-SEMARNAT-2021 for each contaminant.
Keywords: biofilter, organic matter, water regulations, biomaterials, aerobic-anaerobic.

Resumen

Se evaluó un sistema hibrido de biofiltros (SHB) uno anaerobio y el segundo aerobio, conectados en serie y empacados con fibra de agave, subproducto de la fabricación de mezcal artesanal, tratando aguas residuales municipales. Se aplicaron cinco cargas hidráulicas superficiales (CHSs) de 0.27, 0.54, 0.80, 1.07 y 1.34 m^3/m^2d, respectivamente. El suministro de aire fue de 0.62 m^3/m^2h. Primero, se determinó el tiempo de acondicionamiento de la población microbiana sobre el material filtrante. Las otras cuatro CHSs se probaron con el fin de encontrar la máxima capacidad de tratamiento del SHB. Con la CHS de 0.27 m^3/m^2d se alcanzó el acondicionamiento a los 64 días de operación. La máxima eficiencia de remoción de DBO_5 fue 94% (17± 5 mg/L) y DQO 88% (130 mg/L) con la CHS de 0.54 m^3/m^2d. La remoción de SST se mantuvo dentro de la norma a lo largo de la investigación siendo 89% (16 ± 8 mg/L). Con la CHS de 0.80 m^3/m^2d se logró una eficiencia de remoción de coliformes fecales de 4 unidades logarítmicas. Se concluye que un sistema hibrido de biofiltros empacados con material orgánico es eficiente para tratar aguas residuales en comunidades rurales cumpliendo con los valores de la NOM-001-SEMARNAT-2021.
Palabras clave: biofiltración, materia orgánica, normas mexicanas, biomateriales, aerobio-anaerobio.

*Corresponding author. E-mail: jmvigueras@hotmail.com;
https://doi.org/10.24275/rmiq/IA24347
ISSN:1665-2738, *issn-e*: 2395-8472

1 Introduction

Raw wastewater discharged from small communities significantly contributes to global water pollution due to the historical concentration of municipal wastewater treatment plants (MWWTP) in large cities. However, there is a growing recognition of the need for on-site wastewater treatment in rural regions to prevent groundwater and natural aquatic contamination (Kong *et al*., 2016). Meeting environmental standards for water reuse necessitates effective treatment processes, including the removal of organic matter, nutrients, and pathogens.

In rural Durango, wastewater treatment predominantly relies on oxidation ponds, with many releasing untreated wastewater into water bodies, posing environmental risks. To mitigate this, there is a burgeoning interest in biofiltration systems utilizing readily available biomaterials. Biofilters (BFs) with organic beds present a promising solution due to their ease of installation, operation, and cost-effectiveness (Ganesan and Mrudula, 2024). These systems have demonstrated high pollutant removal efficiency in various settings, including rural communities and decentralized treatment plants (Serrano-Meza *et al*., 2020). Biofilters offer a cost-effective solution for wastewater treatment, requiring minimal investment in construction, boasting low operating costs, and proving easy to operate (Ganesan and Mrudula, 2024).

Both aerobic and anaerobic attached growth processes are attractive options for in situ wastewater treatment (Loreto-Muñoz *et al*., 2024). These systems utilize diverse filter media, including peat, wood chips, natural fibers (such as those from palm and coconut shells), as well as compost waste, sugar cane bagasse, sawdust, and husk (Re *et al*., 2024; Awere *et al*., 2023; Ehoussou *et al*., 2024; Costa-Conceicao *et al*., 2023; Escobar *et al*., 2024). The selection of organic materials is based on their availability in the region and cost-effectiveness, ensuring efficient distribution of wastewater flow and avoiding short circuits.

Studies by Vigueras-Cortés *et al*. (2013) and Sosa-Hernández *et al*. (2016) have demonstrated the efficacy of individual aerobic and anaerobic BFs for pollutant removal, with mesquite wood chips showing high removal efficiencies. When biofilters (BFs) are operated individually, they must be either aerobic or anaerobic. It is important to note that BFs operated under aerobic conditions might not remove pollutants that are effectively removed in anaerobic conditions, and vice versa. However, the potential of combining aerobic and anaerobic BFs in series, packed with organic material, remains unexplored. This configuration of connecting biofilters has the potential to enhance the removal efficiency of certain pollutants. As mentioned by Kanafin *et al*. (2021), there are certain compounds present in municipal wastewater that are recalcitrant to either aerobic or anaerobic treatments. When the biofilm process combines multiple processes in series, it forms a hybrid system, resulting in a higher-quality effluent compared to individual operation (Serrano-Meza *et al*., 2022). Hybrid treatment systems, combining various unit operations and processes, hold promise in improving wastewater effluent quality and overall process performance through additive and synergistic effects (Tee *et al*., 2016; Müller *et al*., 2019). Furthermore, according to Wang *et al*. (2022), arranging a treatment system in series with anaerobic conditions preceding aerobic ones could improve removal efficiency. This is because initiating anaerobic treatment initially enhances wastewater biodegradability by facilitating adaptation and providing ample electron donors.

Agave fiber, abundant in southeast Durango due to mezcal production, emerges as a promising filter material. It is cost-effective, environmentally friendly, and promotes biofilm formation, thereby enhancing pollutant removal efficiency. Utilizing such biomaterials in BFs – readily available in Durango – offers an efficient and sustainable approach to mitigating surface water pollution, especially as compared to other methods, such as utilizing PET and decorative flowers (Fernández-Echeverría *et al*., 2022), cold plasma (Almaraz-Vega *et al*., 2022), or photovoltaic systems (Medrano-Hurtado *et al*., 2022). While these types of wastewater treatment processes can be valuable in certain circumstances and locations, they would be less feasible in Durango due to the climatic conditions and the potential cost prohibitive nature of securing specialized equipment in rural communities.

This study aims to evaluate a hybrid system comprising anaerobic and aerobic BFs connected in series for wastewater treatment. Four hydraulic loading rates (HLR) were assessed for their impact on the removal of organic matter, suspended material, and pathogens. The effluent quality was compared to regulatory standards set by Mexican (SEMARNAT 2022) and United States (USEPA 2012) authorities, as well as the results obtained from individual BFs packed with agave fiber. By elucidating the efficacy of hybrid biofiltration systems, this research contributes to the development of cost-effective and environmentally sustainable wastewater treatment solutions.

2 Material and methods

2.1 Municipal wastewater

Random samples of municipal wastewater (MWW) were collected directly from the discharge pipes at

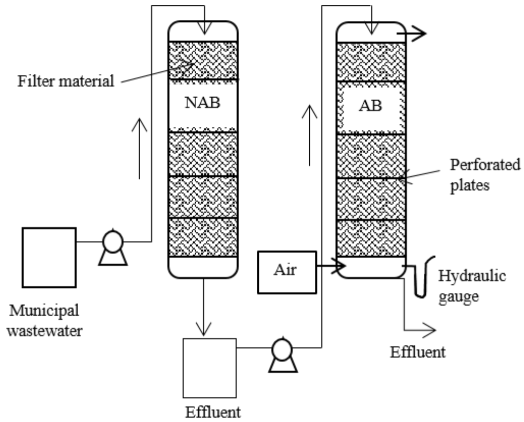

Figure 1. Setup of hybrid biofiltration system packed with agave fiber.

the Orient Wastewater Treatment Plant (WWTP) in Durango, Mexico, during the peak daily mass loading. Samples were collected using a 50 L polyethylene (PE) container and transported to the laboratory. The MWW was introduced at the top of the anaerobic biofilter (ANB), and then the effluent is directed into the aerobic biofilter (AB) using Masterflex peristaltic pumps (Metrohm, Herisau, Switzerland).

2.2 Analytical methods

The following parameters were analyzed following standard methods (Baird *et al*., 2017): BOD_5 using the 5-day test (method 5210); COD by Closed Reflux colorimetric method (method 5220); TSS by Total Solids Dried at 103-105 °C (method 2540); fecal coliforms (FC) by the multiple tube test (method 9230); Electrical conductivity (EC, method 2510); and pH by electrometric method. Additionally, the internal temperature of the biofilters (BFs) was measured daily with a glass thermometer. BOD_5, COD, and TSS were tested in duplicate.

2.3 Setup of the hybrid biofilters system

The biofilters were constructed from 2.0 m high polyvinyl chloride (PVC) tubing with an internal diameter of 0.2 m. They were packed with agave fiber from the *Agave durangensis* plant provided by a mezcal-producing company located in Nombre de Dios, Durango, Mexico. The system comprised two BFs connected in series: an anaerobic biofilter (ANB) that feeds from wastewater and an aerobic biofilter (AB) operating with mechanical aeration. This configuration constituted a hybrid biofiltration system (HBS). The analysis of the results and conclusions were based on the final effluent of this system. The AB received an aeration rate of 0.62 m^3/m^2 h in a countercurrent of MWW flow, monitored daily using a Dwyer RMA-2 flow meter (Dwyer, Michigan City, Indiana, USA). Pressure drop was measured with a hydraulic gauge connected to a pipe. BFs were operated at room temperature throughout.

2.4 Start-up period

A conditioning period for the BFs occurred during start-up, promoting microbial growth (biofilm) in the filter media. MWW was fed to the HBS at a rate of 5 mL/min (corresponding to HLR = 0.27 m^3/m^2d) until BOD_5 concentration in the effluent stabilized within permissible limits (i.e., ≤30 mg/L) as per standard regulations.

2.5 Experimental stages

Following start-up, four flow rates were tested at 10, 15, 20, and 25 mL/min, corresponding to four hydraulic loading rates (HLRs) that are shown in Table II. Each stage concluded when the geometric mean BOD concentration stabilized for 15 days, remaining at or below 30 mg/L in the effluent, meeting Mexican and U.S. regulations for irrigation reuse. The experimental period lasted 360 days. Two variables, "with air" and "without air," were considered based on the HLRs and tested using a factorial design. The factorial design was chosen to understand how aeration and hydraulic loads jointly affect the system's efficiency and to identify their interaction effects. This approach maximizes information while minimizing the number of experiments needed, ensuring efficient use of resources and robust statistical analysis. Insights from a factorial design study are scalable and applicable to similar biofiltration systems, providing a foundation for more efficient and adaptable solutions in various contexts. The internal temperature of the BFs served as a co-variable to isolate its influence on system performance, ensuring accurate assessment of aeration and hydraulic load effects. This is important in environmental studies where temperature fluctuations significantly impact biological processes. Statistical analyses were conducted using Statistica software (StatSoft, Tulsa, OK, USA).

3 Results and discussion

3.1 Wastewater composition

The average composition of the raw wastewater used (Table I) was categorized as medium strength, according to Al-Sulaiman *et al.* (2018), with a BOD_5/COD ratio of 0.35. Hardyanti *et al.* (2023) noted that a BOD_5/COD ratio between 0.1 and 1.0 corresponds to a biodegradable zone, indicating the decomposability of organic matter.

Table I. Average composition of the raw municipal wastewater used.

Parameters	Average concentrations ±S.D.	Units	Number of samples
Biochemical Oxygen Demand	252±37	mgL^{-1}	27
Chemical Oxygen Demand	706±165	mgL^{-1}	29
Total Suspended Solids	146±34	mgL^{-1}	19
Fecal Coliform	$1.26x10^7±2.15x10^7$	MPN/100 mL	35
Electric Conductivity	850±47	μScm^{-1}	31
pH	7.07±0.69	-	30

S.D.=Standard Deviation; MPN=Most Probable Number.

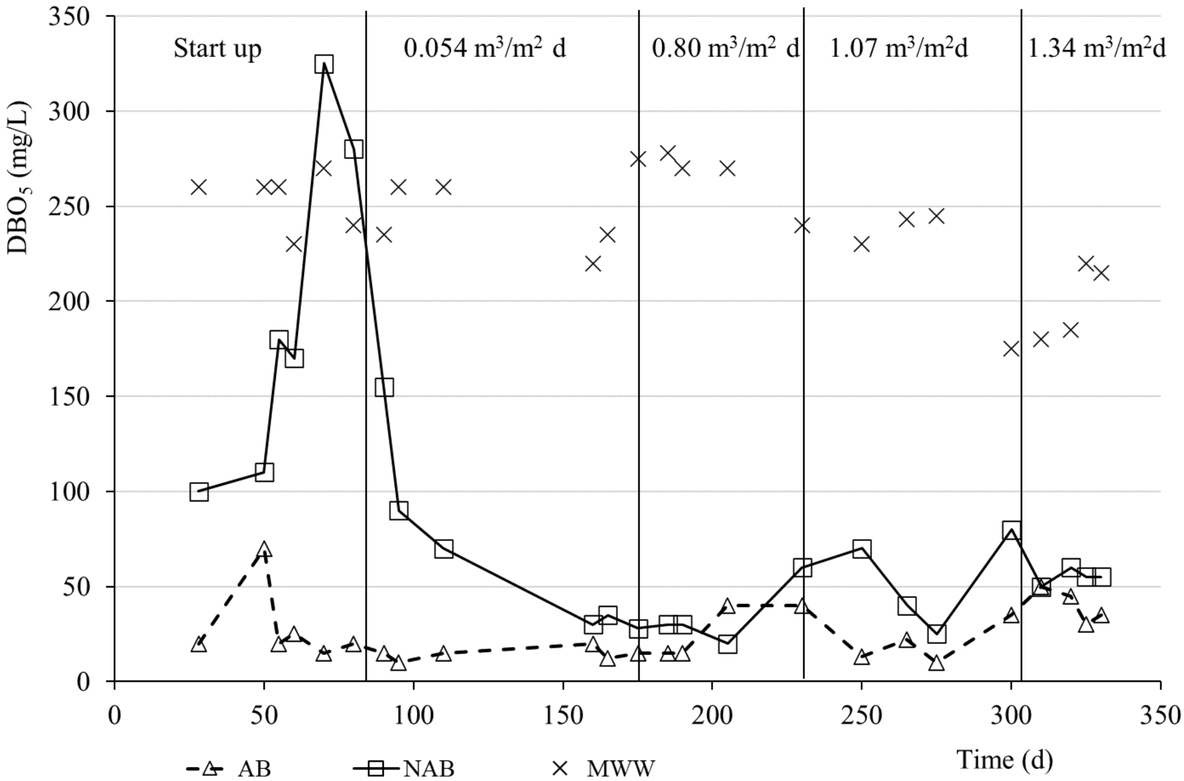

Figure 2. Biochemical oxygen demand concentrations in the hybrid biofilters system evaluated with four hydraulic loading rates.

3.2 Organic matter removal

3.2.1 BOD_5 removal

During the start-up period (HRL = 0.27 m^3/m^2d), the effluent of the NAB had an increase in BOD_5 concentration up to 340 mg/L within the initial 72 days, possibly due to soluble components in the filter material (Martikainen, 2023). Conditioning of the HBS concluded at 64 days, with BOD_5 concentrations dropping below permissible levels of 30 mg/L (Fig. 2). This duration was 30 % shorter than that reported in individual biofilters by Vigueras-Cortés *et al*. (2013) (77 days). The low BOD_5 removal in the NAB at the experiment's outset corresponds to the conditioning phase, likely attributable to the slow growth rate of microorganisms (Singh *et al*., 2023). Additionally, the experimental temperature (<23°C) might affect because according to Rizvi *et al*., (2015), anaerobic processes present greater removal at more than 30°C. The absence of packing material pretreatment (washing) may also have contributed to increased BOD_5 levels due to extracted soluble components.

In the initial experimental stage (HLR = 0.54 m^3/m^2d), the NAB effluent achieved 30 mg/L within 160 days. However, during the conditioning phase (64 startup days), the NAB effluent feeding into the AB maintained a BOD_5 concentration below 30 mg/L and remained stable throughout stage I. Subsequent, the HBS (HLR = 0.80 and 1.07 m^3/m^2d) experimental stages also attained permissible concentrations following aerobic treatment, with BOD_5 concentrations of 32±18 and 39±18 mg/L, respectively (Table II). Finally, the highest BOD_5 removal efficiency (94%) was observed in stage I (HLR = 0.54 m^3/m^2d), achieving an average effluent concentration of 17±5 mg/L BOD_5.

Table II. Average concentration in the effluents of the hybrid biofiltration system.

HLR (m^3/m^2d)	BOD_5 (mg/L)	% R	COD (mg/L)	% R	TSS (mg/L)	% R	FC (Log units)
0.52	17±5	94	299±124		14±8		3
0.80	32±18		129±43		13±9	91	4
1.07	39±18		130±40		17±7		3
1.34	57±18		50±46	93	18±7		3

HLR= Hydraulic Loading Rates; BOD_5 = Biochemical oxygen demand; COD= Chemical oxygen demand; TSS= Total suspended solid; FC= Fecal coliform; %R= removal efficiency; log unit= Logarithm units.

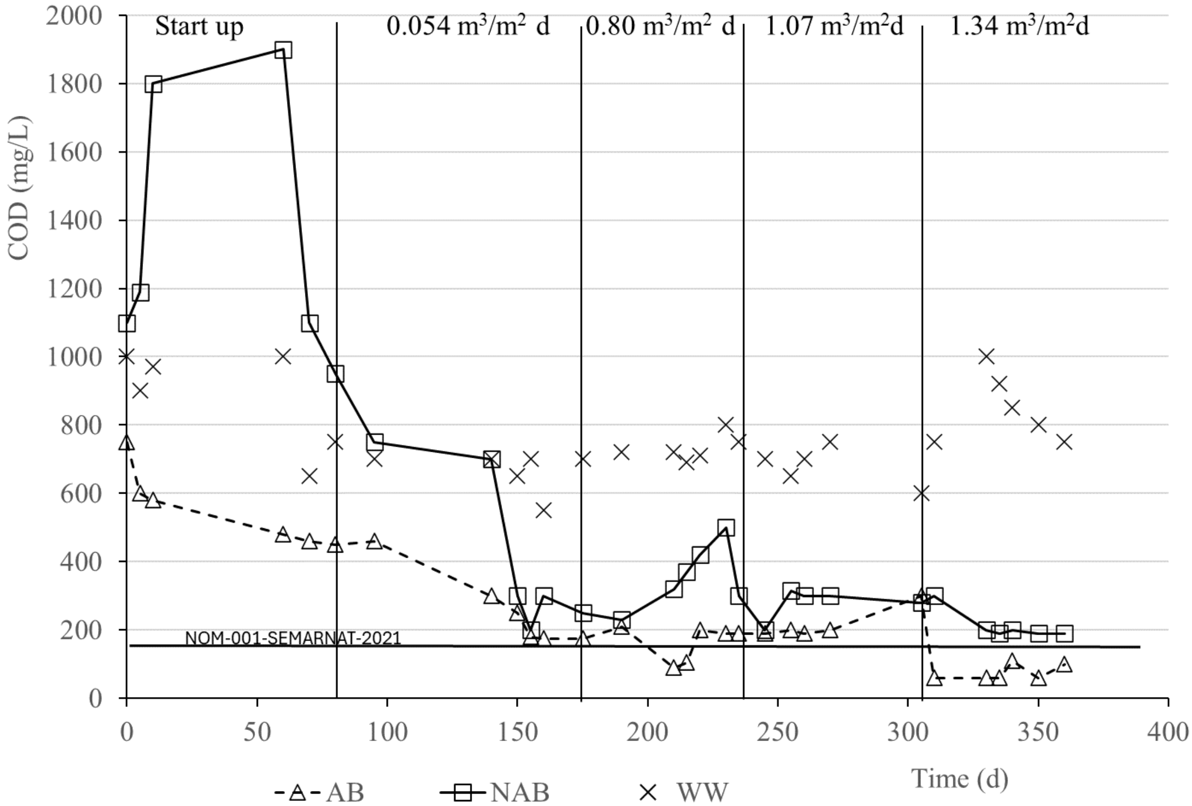

Figure 3. Chemical oxygen demand concentrations in the hybrid biofilters system evaluated with four hydraulic loading rates.

According to covariance analysis, the internal temperature of biofilters, presence of air, and air*HLR interaction significantly influenced BOD_5 removal ($p = 0.001$). Fisher method-based mean analysis revealed that air presence in the HBS exhibited the highest BOD_5 removal efficiency at an HLR of 0.54 m^3/m^2d.

The BOD_5 removal efficiency in the HBS (94%) was higher than that reported by Waqkene *et al*. (2023), who used a biofilter filled with sand and gravel, achieving 46% removal efficiency. Zaheer *et al*. (2023) achieved 88% BOD_5 removal efficiency in anaerobic biofilters filled with walnut shells. Vigueras-Cortés *et al*. (2013) reported a BOD_5 removal of 91% using individual ABs at an HLR of 0.80 m^3/m^2d, using the same filter media as this study. However, this efficiency was similar to the results obtained by Tejedor *et al*. (2020), who achieved 93 % of BOD_5 removal efficiency using wood chips/peanut shells in a single natural aerated BF with a similar HLR (0.5 m^3/m^2d) than the HLRs used in this study (0.54 m^3/m^2d). These results demonstrate that agave fiber is a good filtering material and that the HBS removes higher organic matter than individual biofilters. This system could find application in decentralized plants to treat low wastewater volumes.

3.2.2 *COD removal*

During the start-up phase, COD concentration in the NAB effluent peaked at 2000 mg/L, while influent MWW contained 706±165 mg/L. The rise in COD could be attributed to the dissolution of soluble caramelized carbohydrates and recalcitrant compounds from agave fiber formed during mezcal production. In this period, the HBS exhibited COD removal from 2000 to 400 mg/L (Fig. 3), suggesting that mechanical aeration may accelerate the oxidation of compounds associated with mezcal production.

In the initial experimental stage (Table II), COD significantly decreased below influent levels. From an initial concentration of 1080 mg/L in the NAB, it dropped to 130 mg/L by the end of stage I, achieving an 88% removal efficiency, consistent with the trend observed in BOD reduction during this stage. The standard deviation of COD concentrations in Table II reflects the variability inherent in the wastewater treatment process, influenced by factors such as fluctuating influent characteristics and the evolving biofilm dynamics. In the final experimental stage (Table II), the AB reached the lowest COD concentration of 50 mg/L, corresponding to a 93% removal efficiency. The disparity between stages could be attributed to a more mature biofilm in the AB, better conditioned to remove recalcitrant contaminants, which also contributes to the reduced standard deviation observed in later stages. This indicates that the system stabilizes over time, leading to more consistent COD removal outcomes. This stability is a significant advantage when selecting hydraulic loads for operating the hybrid system.

Covariance analysis revealed that the intercept, temperature, and presence of air were statistically significant ($p = 0.001$) for COD removal. Fisher Method-based mean analysis indicated that the hybrid system with air had the highest COD removal efficiency at an HLR of 1.34 m^3/m^2d.

The COD removal efficiency achieved in this research (93 %) is higher than other studies. Lai *et al*. (2022), assessing stormwater biofilters achieved only 86% COD removal, while Awere *et al*. (2023) reported an average of 69% COD removal with a biofilter packed with Palm Kernel Shell. Similarly, Ghazy *et al*. (2016) achieved 79, 88 and 64% COD removal efficiency using rice straw, date palm fiber, and wood chips in aerated biofilters. Results closest to ours are Almeida-Naranjo *et al*. (2023), who achieved 94% COD removal in biofilters packed with oil palm empty fruit bunch without mechanical aeration at an HLR of 0.5 m^3/m^2d in a full-scale biofilter facility. Even higher COD removal has been achieved using hybrid treatment systems. Kong *et al*. (2016) obtained 86 and 87 % of removal efficiencies using two parallel biofilters for a sulfur/pyrite-based autotrophic denitrification process. Interestingly, Vigueras-Cortés et al. (2013), using the same filter material but with individual biofilters, achieved only 79% COD removal efficiency, lower than our study with the HBS (93%). These findings indicate that biofilters in series are more efficient in COD removal than individual biofilters.

Table III. Microbiota present in Organic Biofilters Packed with Agave Fiber reported by Vigueras-Cortes (2012).

Type of biofilter	Microorganism	Identity (%)
Aerobic	Staphylococcus xilosus	100
	Staphylococcus aureus	95
	Bacillus senegalensis	99
	Clostridium magnum	98
	Clostridium aciditolerans	98
Anaerobic	Pseudomonas putida	100
	Bacillus anthracis	100
	Parvibaculum lavamentivorans	89
	Bacteroidetes bacterium	85
	Salinisphaeraceae bacterium	89

3.2.3 Total suspended solids removal

TSS removal in this study averaged 89%, with an effluent concentration of 16±8 mg/L across all investigated HLRs (Table II). The highest removal efficiency reached 91%, with an effluent concentration of 13±9 mg/L at an HLR of 0.8 m^3/m^2d in the HBS. Both NOM-001-SEMARNAT-2021 (SEMARNAT, 2022) and USEPA (2012) standards stipulate a maximum permissible concentration of 30 mg/L. The TSS removal efficiency was lower than that reported by Zaheer *et al*. (2023), who obtained 94 % using walnut shells as a filter medium. Thus, TSS concentrations in all HLRs of this study comply with Mexican (SEMARNAT, 2022) and United States (USEPA, 2012) regulations, confirming agave fiber's efficiency in suspended matter removal during wastewater treatment.

The removal of organic and inorganic compounds, as measured by BOD_5, COD, and total suspended solids, aligns with the microbiota identified by Vigueras-Cortés (2012) (Table III) in biofilters packed with agave fiber. In these biofilters, *Bacillus senegalensis* and *Clostridium magnum* were present in aerobic conditions, while *Pseudomonas putida*, *Bacillus anthracis*, *Parvibaculum lavamentivorans*, *Bacteroidetes bacterium*, and *Salinisphaeraceae bacterium* were found in anaerobic conditions.

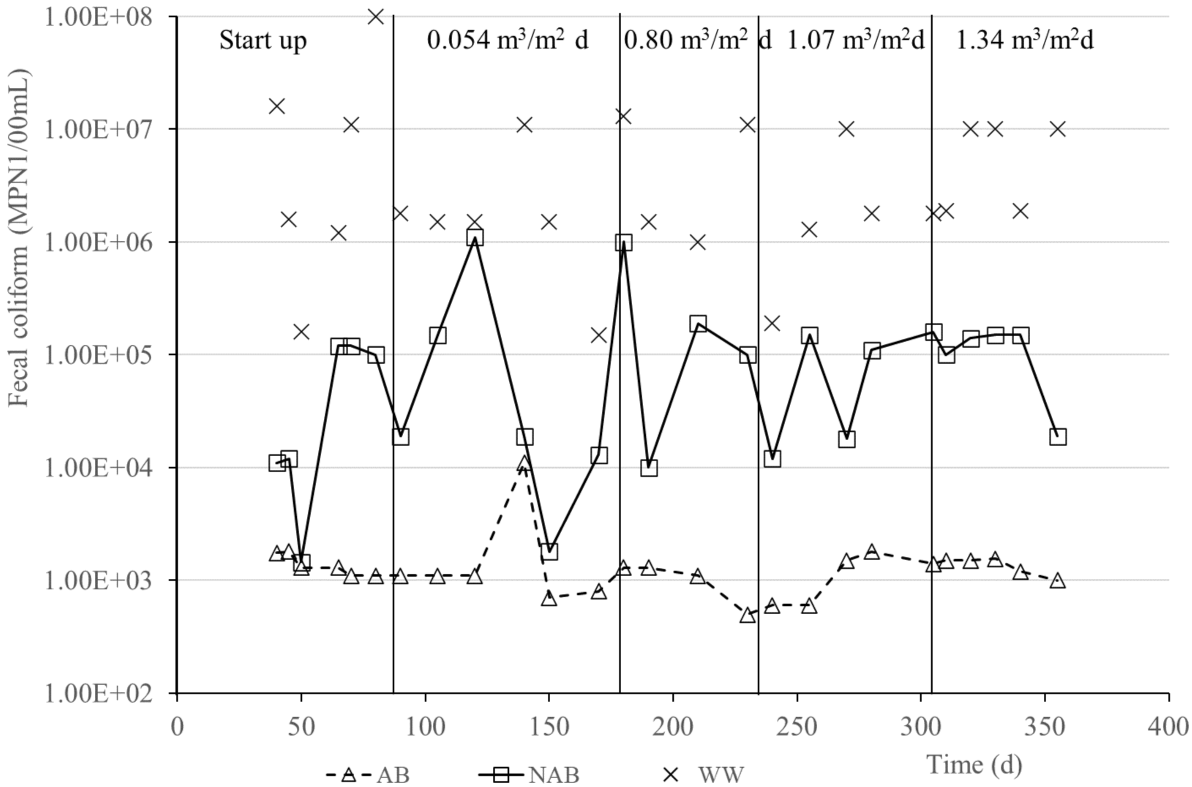

Figure 4. Fecal coliforms concentration in the hybrid biofilters system evaluated with four hydraulic loading rates.

These microorganisms are known to degrade various compounds, including phenols, carbohydrates, surfactants, polysaccharides, alkanes, nitrates, and sulfates (Vigueras-Cortés, 2012).

3.2.4 Fecal coliform removal

The HBS showed FC removal throughout the start-up and experimental stages, achieving 99.8% removal (2 log units) during start-up and 99.8% and 99.98% removal (2 and 3 log units) in the NAB and AB, respectively, in the first and last experimental stages (Table II) (Fig. 4).

In stages I and III, with HLRs of 0.54 and 1.07 m^3/m^2d, respectively, the HBS achieved the maximum FC removal efficiencies of 99.95 % (3 log units). Stage II, with an HLR of 0.80 m^3/m^2d, achieved 4 log units, meeting both Mexican and US EPA standards, although this removal efficiency was temporary. Covariance analysis indicated that the intercept, presence of air, HLR, and air*HLR interaction significantly influenced FC removal ($p = 0.001$). Fisher method-based mean analysis showed that the HLR effect of the hybrid system had the highest FC removal efficiency at an HLR of 0.80 m^3/m^2d.The FC removal efficiency in the BF is attributed to the presence of *testate amoebae*, natural predators that alter FC concentration (Murase and Asiloglu, 2023). Significant FC removal begins once the filtering medium is colonized by biofilm (Zhang *et al.*, 2021). Additionally, Kaetzl *et al.* (2018) achieved up to 1.7 log units removal of fecal indicator bacteria (FIB) with anaerobic BFs packed with spruce woodchips. The HBS's ability to remove FC is comparable to systems with synthetic packing material. The maximum FC removal efficiency observed in the HBS (4 log units) is similar to that obtained by Naz *et al.* (2015), who evaluated polystyrene and stone packing material in biological trickling filters (BTFs), achieving 3 and 4 log units removal, respectively. Lai *et al.* (2022) removed 2 log units with stormwater biofilters. Similarly, an integrated hybrid anaerobic-aerobic sewage treatment system packed with non-woven polyester fabric achieved 3 log units removal of FC (El-Senousy and Abou-Elela, 2017).

Finally, the high FC removal efficiency obtained (4 log units <1000 MPN/100 mL) in the HBS allows effluent use in irrigation of green areas and agriculture, since the effluent complies with Mexican and US EPA standards. It also confirms that the agave fiber is a viable packing material for pathogenic organism removal in biofilters with organic beds during the municipal wastewater treatment, suitable for decentralized stations as a technological alternative.

Conclusions

The hybrid biofiltration system connected in series demonstrated increased pollutant removal efficiency compared to individual biofilters operation. Comparing results to other HBS studies, the system packed with agave fiber provides acceptable effluent during municipal wastewater treatment. Conditioning time in the HBS concluded within 64 days when BOD_5 concentrations fell below permissible levels. The system has significant potential to eliminate pollutants such as BOD_5, COD, TSS, and FC, addressing environmental concerns and human health issues, especially in rural areas. The use of agave fiber in biofilters yielded higher pollutant removal efficiency (94% BOD_5, 93% COD, 91% TSS, and 4 log units FC) than individual biofilter operation. It is concluded that employing a series configuration with the anaerobic condition preceding resulted in an enhanced biodegradability of compounds under aerobic conditions. This was evidenced by improvements in removal efficiencies across all parameters compared to operating individual biofilters. Agave fiber, being readily available, inexpensive, and easy to transport, offers promise for application in wastewater treatment plants in small towns.

Acknowledgements

The present research was financially supported by the Instituto Politécnico Nacional (Project SIP20130563). A. Serrano-Meza is the recipient of a scholarship from the Consejo Nacional de Ciencia y Tecnología (México). Vigueras-Cortés, Juan Manuel is fellows of Estímulos al Desempeño de Investigación (EDI-IPN), y la Comisión de Operación y Fomento de Actividades Académicas (COFAA-IPN).

References

Al-Sulaiman, A. M., and Khudair, B. H. (2018). Correlation between BOD5 and COD for Al-Diwaniyah wastewater treatment plants to obtain the biodigrability indices. *Pakistan Journal of Biotechnology 15*(2), 423-427.

Almaraz-Vega, E., Guevara-Ruíz, D., Sánchez-Castillo, M. A., Sánchez-Díaz, J. C., Martínez, A. and Cruz-Barba, L. E. (2022). Wastewater management using cold plasma–Degradation of organic dyes in liquid phase. *Revista Mexicana de Ingeniería Química 21*(2), 2792-2792

Almeida-Naranjo, C. E., Gallegos, E., Domínguez, E., Gutiérrez, P., Valle, V., Aguilar, A. D., and Vasco, C. (2023). From Renewable Biomass to Water Purification Systems: Oil Palm Empty Fruit Bunch as Bio-Adsorbent for Domestic Wastewater Remediation and Methylene Blue Removal. *Water 15*(23), 4116.

Awere, E., Obeng, P. A., and Bonoli, A. (2023). Application of Palm Kernel Shell Granular Filter Medium for Decolourisation and COD Removal from Clarified Palm Oil Mill Effluent. *International Journal of Environmental Science and Development 14*(5), 329-339.

Baird, R., Rice, E., and Eaton, A. (2017). *Standard methods for the examination of water and wastewaters.* 23rd Ed. American Public Health Association (APHA), American Water Works Association, 1, Washington, DC, USA.

Costa-Conceicao, K., Villamar Ayala, C. A., Dávila, T., and Gallardo, M. C. (2023). Performance of hybrid biofilter based on rice husks/sawdust treating grey wastewater. *Water Science & Technology 87*(10), 2416-2431.

Ehoussou, K. F. D. T., Akotto, A. G., Assémian, A. S., Adou, K. E., Kpidi, Y. H., Ossehein, A., and Ossey, Y. B. (2024). Elimination of ibuprofen and diclofenac by biofiltration on an organic support made from coconut fibers and husks. J. Mater. *Environmental Science 15*(8), 1104-1126.

El-Senousy, W.M. and Abou-Elela, S.I. (2017). Assessment and evaluation of an integrated hybrid anaerobic–aerobic sewage treatment system for the removal of enteric viruses. *Food and Environmental Virology 9*(3), 287-303. https://doi.org/10.1007/s12560-017-9286-4

Escobar, B., Baas-Lopez, J.M., Tapia-Tussel, R. and Olguin-Maciel, E. (2024) Biochar-packed biofilter for the treatment of gases produced by accumulated sargassum waste. *Revista Mexicana de Ingeniería Química 23*(2), 1-8. https://doi.org/10.24275/rmiq/Bio24219

Fernández-Echeverría, E., Herazo, L. S., Zurita, F., Betanzo-Torres, E. and Sandoval-Herazo, M. (2022). Development of Heliconia latispatha in constructed wetlands, for the treatment of swine/domestic wastewater in tropical climates, with PET as a substitute for the filter medium. *Revista Mexicana de Ingeniería Química 21*(2), 2811-2811.

Ghazy, M., Basiouny, M., and Badawy, M. (2016). Performance of agricultural wastes as a biofilter media for low-cost wastewater treatment technology. *Advances in Research 7*(6), 1-13.

Ganesan, S., and Mrudula, P. (2024). Biofilters: An Organic Approach to Wastewater Treatment. In: *Sustainable Water Treatment and Ecosystem Protection Strategies*, pp. 277-287. Apple Academic Press. New York.

Hardyanti, N., Susanto, H., Budihardjo, M. A., and Saputra, A. T. (2023). Characteristics of Tofu Wastewater From Different Soybeans and Wastewater at Each Stage of Tofu Production. *Ecological Engineering & Environmental Technology 24*.

Kaetzl, K., Lübken, M., Gehring, T. and Wichern, M. (2018). Efficient low-cost anaerobic treatment of wastewater using biochar and woodchip filters. *Water 10*, 818. https://doi:10.3390/w10070818.ID

Kanafin, Y. N., Kanafina, D., Malamis, S., Katsou, E., Inglezakis, V. J., Poulopoulos, S. G., and Arkhangelsky, E. (2021). Anaerobic membrane bioreactors for municipal wastewater treatment: a literature review. *Membranes 11*(12), 967.

Kong, Z., Li, L., Feng, C., Dong, S. and Chen, N. (2016). Comparative investigation on integrated vertical-flow biofilters applying sulfur-based and pyrite-based autotrophic denitrification for domestic wastewater treatment. *Bioresource Technology 211*, 125—135. https://doi.org/10.1016/j.biortech.2016.03.083

Lai, S. H., Bu, C. H., Chin, R. J., Goh, X. T., and Teo, F. Y. (2022). New approach to predict fecal coliform removal for stormwater biofilters application. *IIUM Engineering Journal 23*(2), 45-58.

Loreto-Muñoz, C.D., López-Avilés, G., De la Cruz-Leyva, M.C., Martin-García, A.R. and Almendariz-Tapia, F. J. (2024). Sulfidogenic activity related to microbial diversity in a biological system employed for sulfate-rich wastewater treatment. *Revista Mexicana de Ingeniería Química 23*(1), 1-11. https://doi.org/10.24275/rmiq/IA24167

Martikainen, K. (2023). Wastewater treatment in rural areas: Functionality of sand filters and suitability of filter media for reuse. Doctoral dissertation in Science, Forestry and Technology, University of Eastern Finland, Finland.

Medrano-Hurtado, Z. Y., Medina-Aguirre, J. C., Marcelo-Medrano, H., Castillón-Barraza, A., Zamora-Alarcón, R., Casillas-Lamadrid, M. E., Jumilla-Corral, A.A. and Mayorga-Ortiz, P. (2022). Domestic wastewater treatment by electrocoagulation system using photovoltaic solar energy. *Revista Mexicana de Ingeniería Química 21*(2), 2809-2809.

Müller, J., Drewes, J.E., and Hübner, U. (2019). Investigating synergies in sequential biofiltration-based hybrid systems for the enhanced removal of trace organic chemicals from wastewater treatment plant effluents. *Environmental Science: Water Research & Technology 5*(8), 1423-1435. https://doi.org/10.1039/C9EW00181F

Murase, J., and Asiloglu, R. (2023). Protists: the hidden ecosystem players in a wetland rice field soil. *Biology and Fertility of Soils*, 1-15.

Naz, I., Saroj, D.P., Mumtaz, S., Ali, N. and Ahmed, S. (2015). Assessment of biological trickling filter systems with various packing materials for improved wastewater treatment. *Environmental Technology 36*(4), 424-434. https://doi.org/10.1080/09593330.2014.951400

Re, A., Schiavon, M., Torretta, V., Polvara, E., Invernizzi, M., Sironi, S., and Caruson, P. (2024). Application of different packing media for the biofiltration of gaseous effluents from waste composting. *Environmental Technology 45*(8), 1622-1635.

Rizvi, H., Ahmad, N., Abbas, F., Bukhari, I.H., Yasar, A., Ali S., Yasmeen, T. and Riaz, M. (2015). Start-up of UASB reactors treating municipal wastewater and effect of temperature/sludge age and hydraulic retention time (HRT) on its performance. *Arabian Journal of Chemistry* 8, 780-786. https://doi.org/10.1016/j.arabjc.2013.12.016

SEMARNAT (2022). *Norma Oficial Mexicana NOM-001-SEMARNAT-2021.* Que establece los límites permisibles de contaminantes en las descargas de aguas residuales en cuerpos receptores propiedad de la nación (That establishes the permissible limits of contaminants in the discharge of wastewater into receiving bodies owned by the nation). Published in Diario Oficial de la Federación on March 11, Mexico City, Mexico.

Serrano-Meza, A., Garzón-Zúñiga, M.A., Barragán-Huerta, B.E., Estrada-Arriaga, E.B., Almaraz-Abarca, N. and García-Olivares, J. G. (2020). Anaerobic digestion inhibition indicators and control strategies in processes treating industrial wastewater and wastes. *Revista Mexicana de Ingeniería Química 19*(1), 29-44. https://doi.org/10.24275/rmiq/IA1221

Serrano-Meza, A., Garzón-Zúñiga, M.A., Moreno-Andrade, I., Barragán-Huerta, B.E., Estrada-Arriaga, E.B., Vigueras-Cortés, J.M. and García-Olivares, J.G. (2022). Hydrogen and methane production from tequila vinasses in a novel hybrid reactor containing biofilm and suspended biomass. *BioEnergy Research 15*(3), 1675-1690. https://doi.org/10.1007/s12155-021-10361-6

Singh, A., Singh, A., Karwariya, S., Pandey, G., Kanga, S., & Singh, S. K. (2023). Correlation Between Volumetric Loading Rate and Removal Efficiency of Bio-chemical Oxygen Demand and Chemical Oxygen Demand for Waste Water Treatment by Improved Bio-tower Technology in Ganga River Basin (India). In: *Climate Change, Agriculture and Society: Approaches Toward Sustainability*, pp. 213-225. Springer International Publishing, Cham.

Sosa-Hernández, D.B., Vigueras-Cortés, J.M. and Garzón-Zúñiga, M.A. (2016). Mesquite wood chips (Prosopis) as filter media in a biofilter system for municipal wastewater treatment. *Water Science and Technology 73*(6), 1454-1462. https://doi:10.2166/wst.2015.595

Tee, P.F., Abdullah, M.O., Tan, I.AW., Rashid, N.K.A., Amin, M.A.M., Hipolito, C.N. and Bujang, K. (2016). Review on hybrid energy systems for wastewater treatment and bio-energy production. *Renewable and Sustainable Energy Reviews 54*, 235-246. https://doi.org/10.1016/j.rser.2015.10.011

Tejedor, J., Cóndor, V., Almeida-Naranjo, C. E., Guerrero, V. H., and Villamar, C. A. (2020). Performance of wood chips/peanut shells biofilters used to remove organic matter from domestic wastewater. *Science of the Total Environment 738*, 139589.

USEPA (2012). *Guidelines for Water Reuse (EPA/600/R-12/618)*. U.S. Environmental Protection Agency, Washington, DC.

Vigueras-Cortés, J.M. (2012) Innovación tecnológica para tratamiento de aguas residuales domesticas con biofiltros orgánicos. Tesis de Doctorado en Ciencias en Biotecnología, Instituto Politécnico Nacional, México.

Vigueras-Cortés, J.M., Villanueva-Fierro, I., Garzón-Zúñiga, M.A., Návar-Cháidez, J.J., Chaires-Hernández, I. and Hernández-Rodríguez, C. (2013). Performance of a biofilter system with agave fiber filter media for municipal wastewater treatment. *Water Science and Technology 68*(3), 599-607. https://doi:10.2166/wst.2013.285

Wang, W., Chang, J.S., Show, K.Y. and Lee, D.J. (2022). Anaerobic recalcitrance in wastewater treatment: A review. *Bioresource Technology 363*, 127920. https://doi.org/10.1016/j.biortech.2022.127920

Waqkene, T., Mereta, S. T., Terfe, A., & Ousman, W. Z. (2023). Integrated methods for household greywater treatment: modified biofiltration and phytoremediation. *Journal of Environmental and Public Health 2023*(1), 7778240.

Zaheer, M., Ali, M. S., Huang, N., and Ashraf, M. A. (2023). Using walnut shells as low-cost adsorbent materials in an anaerobic filter medium of a De-centralized wastewater treatment system (DEWATS). *Chemosphere 341*, 140080.

Zhang, Y., He, Y., Sakowski, E. G., and Preheim, S. P. (2021). Influence of Simplified Microbial Community Biofilms on Bacterial Retention in Porous Media under Conditions of Stormwater Biofiltration. *Microbiology Spectrum, 9*(2), e01105-21.