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RESEARCH ARTICLE

Moving Bed Biofilm Reactor (MBBR) for decentralized grey water treatment: Technical, ecological and cost efficiency comparison for domestic applications

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ABSTRACT

The reuse of greywater has several advantages, including reduced freshwater extraction from rivers, aquifers, and groundwater; reduced need for desalination; less environmental impact from septic tanks and water treatment plants; decreased energy consumption; and reduced chemical pollution. The main objectives of this review study are to assess the technical attributes, ecological impacts, and cost-efficiency of Moving Bed Biofilm Reactor (MBBR) water treatment technology compared to similar available technology for small to medium-sized, decentralized applications in residential and commercial settings such as home gardening, sanitation, and landfills. Previous studies indicate that hybrid technologies such as MBBR are the most promising methods for the total removal of contaminants in wastewater in a decentralized setting. However, the initial capital cost of this technology for small and medium-scale domestic applications worldwide is high and so is a limiting factor in the expansion of its utilization. Expansion of domestic use of such Decentralized Wastewater Treatment Systems (DWTS) could increase the economies of scale and therefore reduce the initial capital costs for this useful water treatment. For the MBBR system, Chemical Oxygen Demand (COD) removal efficiency was found to be 70%, Total Suspended Solids (TSS) removal was found to be 97%, and turbidity removal was 98%.

Keywords: Water Treatment; Moving Bed Biofilm Reactor (MBBR); Decentralized, Technical; Ecological; Efficiency; Cost; Gardening, Domestic Reuse; Membrane Bioreactor (MBR)

BACKGROUND

The United Nations Educational, Scientific, and Cultural Organization (UNESCO) declared that the earth's freshwater resources could meet the water needs of the world's expanding population if managed effectively and sustainably. However, water scarcity and water quality degradation are considerable challenges. Water quality degradation is the greatest threat to the health of ecosystems and people all over the planet which requires prompting immediate action to maintain the health of our ecosystems (Connor, 2015).

The definition of various qualities of water levels or water footprints is classified into green water, blue water, greywater, and blackwater. Green water is the water from precipitation stored in the soil root zone that has evaporated, transpired, or been incorporated by plants. It is particularly relevant for horticultural, agricultural, and forestry products. Bluewater is water sourced from surface or groundwater resources and is either evaporated, incorporated into a product, taken from one water body, returned to another water body, or returned at a different time. Bluewater is relevant for domestic, industry, and irrigated agriculture purposes (Fig. 1). Greywater is wastewater generated in households or office buildings and commercial sites from streams without fecal contamination. Greywater is generally wastewater from showers, baths, basins, and washing machines and shows promising results for water reuse and recycling. In the sanitation context, blackwater is the wastewater from toilets, which likely contains pathogens. Blackwater can contain feces,

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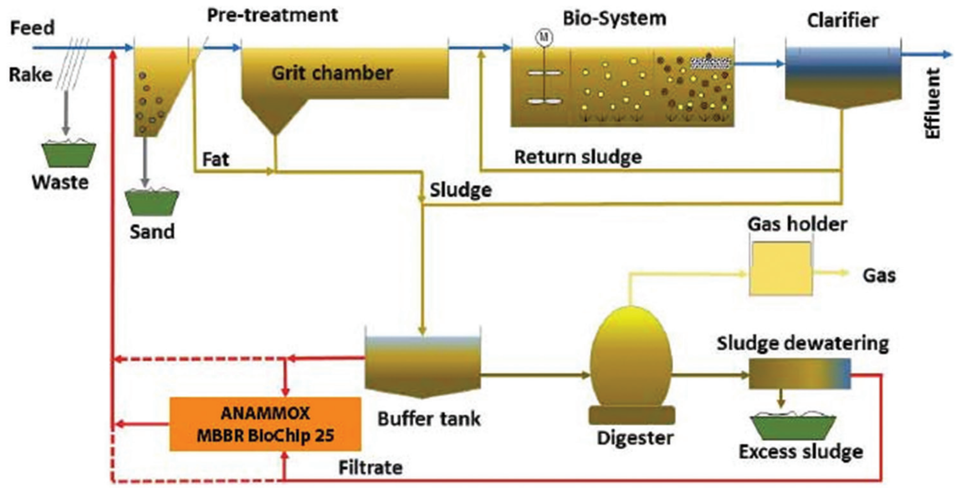

Fig 1. Wastewater treatment process three steps - primary, secondary, and tertiary. Source: Copyright https://www.ecologixsystems.com/system-mbbr.

urine, water, and toilet paper (Cheremisinoff, 2001). This review study targets exploration of the use of advanced technology for greywater treatment and the technical and economic efficiency of using Moving Bed Biofilm Reactor (MBBR) Technology for domestic applications. As previously mentioned, the reuse of greywater has several advantages, including reduction of environmental impacts, chemical pollution, and energy usage. Further, it also reduces the need for water extraction and desalination. Greywater can also be used for groundwater recharge and reclamation of nutrients. Wastewater is continuously increasing in volume due to the increase in domestic and industrial water consumption. The high cost of water transportation, among other emerging environmental issues, makes the topic of water reuse and wastewater recycling increasingly important.

The objective of this study is to evaluate the technical, ecological, and economic (cost and scaling) impacts of water treatment technology MBBR for domestic applications such as reuse for sanitation and gardening. This review study uses previous studies from referee journals, books, and relevant international organizations' reports during the period 2000 to 2021.

This paper is divided into four sections. The first section includes the background and research objective, a definition of the MBBR structure, and characteristics, along with comparing the MBBR to other similar wastewater treatment systems. The second section discusses the MBBR system structure. Section three discusses the technical, ecological, and economic efficiency (considering initial starting cost and economic benefits) of MBBR for domestic applications. Meanwhile, section four summarizes the findings and summarizes the efficiency and limitations of the MBBR system.

MOVING BED BIOFILM REACTOR (MBBR) SYSTEM

The Bed Biofilm Reactor (MBBR) System includes the below main components:

System structure

Conventional wastewater treatment consists of three main steps – primary, secondary, and tertiary. The primary treatment involves the removal of solids by sedimentation or flotation. Secondary treatment consists of the removal of organic matter through microbial decomposition. Tertiary treatment is any additional treatment that the wastewater might undergo if recycled, discharged to the environment, or reused.

The MBBR Water Treatment System includes the following main components:

- **Clarifier** is a settling tank built for the removal of solids being deposited by sedimentation and is used to remove suspended solids or solid particulates from the liquid that is present because of treatment, in this case, from greywater. The concentrated impurities discharged from the bottom of the settling tank are referred to as sludge, where the small particles that float to the surface of the liquid (greywater) are referred to as scum.
- **Chemical feed** is a step where various types of chemicals components are added to the reaction tank to remove the bulk suspended solids materials and other various contaminants to help facilitate the flocculation, precipitation, or coagulation of any metals and suspended solids. The process starts with adding mixing reactors assortments, usually one or two reactors, that add specific chemicals components to take out all the finer particles in the water by

combining them into heavier particles that settle. The most widely used chemicals are aluminum-based, such as alum and poly aluminum chloride.

- **Filtration** is the process where the solid particles in a liquid (greywater) or gaseous fluids are removed by using a filter medium that permits the fluids to pass through but retains the solid particles. In the MBBR system, filtration is used to remove all the leftover trace amounts of suspended solids. The level of the needed filtration will depend on the degree of suspended solids removal required to pass local discharge regulations.
- **Final pH adjustment** and any post-treatment process are where a pH adjustment system is added to adjust the acidity (pH) of the process stream into a defined acceptable discharge pH range. Usually, caustic (NaOH) is added to the stream to pH neutralize the solution.
- **Control panel is used** to control the treatment system's operations depending on the level of automation needed.

Several technologies are in use to tackle the challenge of water treatment quality for decentralized applications. Table 1 below lists the water treatment applications considered for the comparison in this study. The table clearly shows that water treatment and reuse using MBBR technology may have higher positive technical and ecological outcomes when compared to Submerged Aerobic Fix Film (SAFF) and conventional Membrane Bioreactor (MBR). This study details such advantages and limitations of applying MBBR for domestic water treatment applications.

Wastewater analysis

Two analyses have been conducted on two types of water footprints, wastewater & landfill leachate, to study their characteristics. The total amount of wastewater treated = 1000 Kilo Liters per Day (KLD); Table 2 below show the results.

Wastewater unit cost

The cost of one unit for the MBBR System for greywater treatment is shown in Table 3. The cost includes the primary equipment cost and the operation cost for two years per unit.

DISCUSSION ON TECHNICAL, ECOLOGICAL, AND ECONOMIC EFFICIENCY OF THE MOVING BED BIOFILM REACTOR (MBBR) FOR DOMESTIC APPLICATIONS

Various research papers that discussed using and implementing MBBR for domestic applications for treating wastewater were examined. The analysis of these research papers is as follows.

Technical efficiency of the moving bed biofilm reactor (MBBR):

While evaluating the performance, merits, and limitations of the different Decentralized Wastewater Treatment Systems' (DWTS), a paper showed that the membrane-based technologies applied in wastewater treatment as well as in greywater treatment guarantee superior quality of effluent, which ensures greywater reuse guidelines for non-potable purposes are met. Hybrid technologies such as the electrically enhanced biomass concentrator reactor and physical integration of bio-electrochemical systems with biological methods such as microbial fuel cells were the most promising methods for near-complete removal of pollutants from wastewater. Membrane fouling was reduced

Table 1: Comparison of SAFF, MBR, and MBBR Greywater Treatment Technologies

Water Treatment Technology	Technology Description	Ecological Impact and Cost
Submerged Aerobic Fix Film (SAFF)	Submerged Aerobic Fixed Film Reactor (SAFF) has been described as a cost-effective method of sewage sanitation and wastewater treatment that is primarily used in residential and commercial complexes. SAFF process is an attached growth-type aerobic biological process that uses corrugated inert Ultraviolet (U.V.) stabilized Polyvinyl Chloride (PVC) media (Chaudhari et al., 2008).	The (SAFF) is considered a hybrid technology that is gaining attention due to its high treatment efficiency with an added advantage of low footprint area and less operation and maintenance costs. It is comprised of a column or tower packed with media for biofilm growth and a diffused aerator to supply oxygen et al., 2019).
Membrane Bioreactor (MBR)	(MBR) A membrane bioreactor combines a membrane process using microfiltration or ultrafiltration with a biological wastewater treatment process. It is widely used in the industrial and municipal treatment of wastewater (Ma et al., 2018).	(MBRs) Membrane bioreactors have attracted attention in water reclamation because of the cost reduction and recent technical advances in membranes. However, the increasing of micropollutants in wastewaters has posed new challenges (Ma et al., 2018).
Moving Bed Biofilm Reactor (MBBR)	The system consists of an aeration tank with plastic carriers to provide a surface to allow it to grow. The material used in the carriers has a density close to the density of water (1 g/cm). An example is a high-density polyethylene (HDPE), which is close to 0.95 g/cm (Van Lubbe, 2012).	MBBR has lower sludge production, requires less area, and is considered resilient to toxic shock. MBBR is a biological technique, when combined with chemical treatment, and has attracted a great deal of attention for the removal of organophosphorus pesticides from wastewater (Chen et al., 2007).

Table 2: Wastewater Treatment using MBBR System Characteristics

Characteristics	Range
pH	7.8 to 8.01
Turbidity	10 to 120 Nephelometric Turbidity Unit (NTU)
biological oxygen demand (BOD)	30 mg/l
Chemical Oxygen Demand (COD)	200 mg/l
Total Suspended Solids (TSS)	10 mg/l
Oil & Grease	5 mg/l
Chloride	3.5 to 120 mg/l
Alkalinity	15 to 80 mg/l
Total Iron content	0 to 3 mg/l
Zinc content	0.1 to 2 mg/l

Source:(Srivastava, Masud, & Farooque)

Table 3: MBBR System 5m^3/Day for Greywater Treatment Decentralized Unit Cost

Item Name	Specification	Unit USD Price
5 m^3/day MBBR System	Capacity: Average 5m^3/day, Maximum 8 m^3/Day Container, 2mm thickness All-in-one; Automatic running, MBBR moving bed Modular (Screen, Equalization Tank, Anoxic Tank, MBBR with moving Bed Tank, Central Tube, Chlorine Contact Tank, Filtration Tank with MBBR media, and Sludge Holding Tank)	20,800
MBBR Media and spare parts for operation	Water Level Detector, 5 unit	40
	MBBR Media for 2 years	900
	E-valve, two units	100
Total		21, 840

Source: Authors personal contacts with Greywater Treatment System Providers January to August 2021)

to a significant extent. From the study, we can conclude that integration of membrane technology with Microbial fuel Cells (MFCS) is the most effective technology in treating wastewater among all discussed methods such as Submerged Aerobic Fix Film (SAFF) and Moving Bed Biofilm Reactor (MBBR). However, attention should be given to treating wastewater containing pollutants like dyes, leachate, heavy metals, and sulfate (Bajpai et al., 2019).

Numerous studies were conducted on different technologies treating greywater, which vary in complexity and performance. However, there are no specific guidelines for greywater reuse. Also, it is rare to find studies on the evaluation of the appropriate technologies for greywater reuse/recycling. Therefore, a review study examined the treatment alternatives for greywater reuse by reviewing the published literature and evaluating and selecting the proper techniques for greywater treatments and reuse. The authors found out that there is good biodegradability in all types of greywaters. The bathroom and the laundry greywater are deficient in phosphorus and nitrogen, while the kitchen's greywater has a balanced Chemical Oxygen Demand (COD): N: P ratio. Results of this study show that physical processes are not sufficient to adequately reduce the organics, surfactants, and nutrients alone. The chemical processes can efficiently remove the organic materials, suspended solids, and surfactants in low-strength greywater. The MBR appears to be a desirable solution in collective urban residential buildings. The authors proposed a non-potable urban greywater reuse standard and evaluated the treatment alternatives according to greywater characteristics and the proposed measure (Srivastava et al., 2021).

A study titled "Review of the Technological Approaches for Greywater Treatment and Reuses" focused on finding a simple treatment technology to operate with minimum energy consumption and treat greywater for irrigation. The greywater source was obtained from a dormitory at the Jordan university campus's waste streams, including shower, laundry, and washbasins that are redirected into a single outlet pipe to the sewer. The pilot plant consisted of two polyvinyl chlorides (PVC) tanks: the anaerobic and the second aerobic units. Two approaches were tested for aerating the aerobic tank. The first approach was natural aeration aimed at direct contact of liquid and sludge with the air. The second approach uses mechanical aeration by pumping air continuously. This study indicated that the anaerobic unit was operated for 871 days, during weekdays, at three different operational modes. One of these modes includes a fed-batch mode with varying inflow rates over the day. The flow during the batch mode, after filling the tank, was discharged to the sewer with constant liquid reactor volume and varying inflow rates, and varying liquid reactor volume. The outcome of this study offered recommended optimization system consisting of an anaerobic unit operated in up-flow mode. In such a system, it can optimize a one-day operational cycle, a constant effluent flow rate, and varying liquid volume. The COD (Chemical Oxygen Demand) subtraction can be optimized by the anaerobic and aerobic units in summer and winter is 45%, 39%, and 53%, 64%, respectively, with a sludge concentration of 168 and 8 mg, respectively, and stability of 80% and 93%, respectively, based on COD. Aerobic effluent quality, except for pathogens, agrees with the proposed irrigation water quality guidelines for reclaimed water in Jordan (F. Li et al., 2009).

Authors of the paper titled "Greywater Treatment in a Series Anaerobic-aerobic System for irrigation" found the importance of determining the process design parameters for biofilm reaction kinetics, biofilm characteristics, optimization of pollutant removal efficiencies for greywater treatment by Rotating Biological Contactors (RBC) for reuse using GPS-X (version 5.0). RBCs are modular, multipurpose environmental modeling for the simulation of municipal and industrial wastewater treatment plants. The performance and treatment capability of RBC to treat the greywater can be investigated by using the mathematical model. The greywater (wastewater) used in this study was collected from lodging buildings. In this case, the drainage system was segregated as blackwater and greywater streams. Activated sludge taken from an MBR operated with greywater was added to the RBC reactor to adjust and accelerate biofilm growth on the discs at the initial stage of the operation. The results showed that the treatment efficiency of the RBC system based on the Biological Oxygen Demand (BOD) subtraction ranged between about 93.0% and 96.0%. Total Suspended Solids (TSS) subtraction ranged between about 84.0% and 95.0 % for all concentrations of influent greywater. The proposed model results indicated that greywater can be properly treated by an RBC system. Furthermore, the system would be reused for many purposes after disinfection and sand filtration. It has proved several advantages over other greywater management technologies in terms of cost, ease, and low technical personnel requirements (Ghunmi et al., 2010).

A study by (Abdel-Kader et al., 2013) combines a membrane filtration system and a moving bed biofilm reactor in one tank. The Moving Bed Biofilm Membrane Reactor (MBBMR)system was functioning for 10 months. This is a synthetic low and high strength greywater system. This study described the performance of this reactor type on a single-household scale and presented operational aspects and costs as well. The treated effluent of outcome achieved NSF (International Standard/American National Standard) reuse guidelines. The configuration of the process showed to be feasible for implementing onsite microsystems with high flow and load variation. The mean flux of the membrane during the permeating phase was 12.9 L/m2 h. Additionally, natural hair color could be detached by almost 80%, and the pilot unit energy consumption was optimized to less than 1.3 kW h/m3 during the operation. This study results lead to the conclusion that this reactor type could be feasible for greywater treatment for single households (Abdel-Kader, 2013).

Meanwhile, (Abornig et al., 2013) noticed very little published data on the quality of reclaimed wastewater in the UAE. This study assessed the bacteriological quality of reclaimed wastewater used to irrigate thirty public parks in Dubai and Sharjah. It also used Bismuth Sulphite Agar (BSA) technique and Violet Red Bile Agar (VRBA) media to assess the bacterial contaminants using membrane filtration. This study showed the presence of Salmonella, Shigella, E. Enterobacter aerogenes, coli, and other unnamed bacterial species (UBS) on various selective media with different occurrence rates. The most common types of bacteria observed on the BSA media were E. coli (30%), Shigella (63%), Salmonella (10%), and a large fraction of unknown bacteria (97%). The most common bacteria detected on VRBA media were E. coli (83%), unknown bacteria (76%) followed by Enterobacter aerogenes (70%). This study proved that only 40% of the retrieved wastewater (greywater) samples examined complied with the widely accepted international standards and the local standard of less than 1000 fecal coliforms/100mL for unrestricted irrigation (Jabornig and Favero, 2013).

In another study, the authors (Saidi et al. 2017) provided a wide overview of decentralized wastewater treatment systems (DWTS), existing technologies, and their use of domestic wastewater. This study reviews the literature to compare various treatments using Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis. The study explored emerging technologies in decentralized treatment. The findings of this paper were that the membrane-based technologies assured superior quality of effluent, which ensures greywater reuse guidelines for non-potable purposes are met. The study can infer that the integration of membrane technology with MFCs is the most effective technology in treating wastewater among all discussed methods. However, the attention now should be given to treating wastewater encompassing pollutants like dyes, leachate, heavy metals, and sulfate. Several studies on Brief Cognitive Rating Scale (BCRs) technology show that BCRs are simpler, economically feasible, and ensure higher effluent quality than MBRs (Saidi et al., 2017).

Another study compared decentralized treatment technologies for sewage and greywater reuse and reviewed the MBR applications for greywater treatment. This study included publications during the last decade, particularly relevant to the membrane bioreactor, membrane biological reactor, sustainability, reuse reclaimed water, and proposed feasible alternatives. Furthermore, the application of MBR for greywater treatment in a Fit-for-purpose (FfP) approach considers existing non-potable reuse standards and their different specifications. The outcomes of this paper were that MBRs had been identified as a successful general approach to this purpose, able to operate at highly variable chemical oxygen demand (COD) loadings and with influents from different sources while constantly finding high-quality effluents. These systems have been confirmed to be effective in these applications even at low HRTs (Escherichia coli) and extremely low sludge retention time (SRTs). Effluents could easily meet international standards/guidelines for non-potable reuse, save for the possible microorganisms' presence, which would need an additional disinfection stage. Small footprint and effluent quality suggest the application of MBR technology in decentralized applications, with specific attention on single-house or cluster onsite reuse. The flexibility of MBR technology and its easy integration with other processes could allow the development of tailored or "fit-for-purpose" water reuse applications that are preferred now because they foresee treatment flexibility according to needs. Nevertheless, some remaining issues, such as the relatively high investment, operation, and maintenance costs, are still present (Bajpai et al., 2019).

A study published in 2019 by (Cecconet D et al. 2019) found that very few attempts have been made to model full-scale reactors even though many studies have tried to use activated sludge models to improve the MBBR efficiency. This paper applied an activated sludge model (ASM3) to a full-scale multistage MBBR, which operates with PUF bio carriers to treat greywater. MBBR performance was assessed, and then data related to the characterization of the greywater were collected over five months to be investigated using an applied model that describes the system's behavior and fits the experimental results. Results showed that the reactor performed to a high level in removing the (COD) Chemical Oxygen Demand, (DOC) Dissolved Organic Carbon, (BOD5) biological oxygen demand, (NH4-N) ammonia, and (TN) total nitrogen with an overall removal efficiency of 93%, 80.7%, 99%, 89%, and 77%, respectively. The modeling results showed a good correlation between simulated and experimental concentrations of chemical oxygen (COD) demand issued from different reactors of the MBBR system. The adaptability of the ASM3 model fits other parameters such as NH4-N and TN. The dissolved oxygen (D.O.) and Total Suspended Solids (TSS) were also investigated for two selected reactors: reactor (R1) and reactor (R5). The simulation results showed an acceptable correlation between the investigated parameters' evolution in R1 and R5 and the effluent, except for total nitrogen (TN). The stoichiometric parameters adjustment led to a good simulation of TN. Concentrations and the use of dynamic simulation could be the next step for the calibration and validation of the model (Cecconet et al., 2019).

Meanwhile, another paper studied the characteristics and design of primary and secondary treatment units as well as the reuse of produced wastewater. It was found that disposal of untreated wastewater to the natural environment and use for irrigation causes problems for the people and the environment. Raw wastewater samples were collected and analyzed for twenty-three quality parameters: Total Suspended Solids (TSS), total dissolved solids, totally volatile and non-volatile solids, total acidity, total alkalinity, etc. Results showed that some parameters such as BOD5 and TSS exceeded the standards for disposal of wastewater. Collected wastewaters were also noticed as weak to medium wastewater with a greater than 50% biodegradability ratio; thus, it can be inferred that wastewater needs proper treatment processes. Primary treatment processes (such as screening, grit chamber, and flow equalization) and biological treatment processes (i.e., CAS, SBR, and MBBR) were designed and studied. Results revealed that MBBR was the optimal and most economical technique for the biological treatment of wastewater. Treated wastewater is suitable for reuse, and there is no restriction on use for irrigation of green areas inside the Ashty city campus (Yapıcıoğlu, 2019).

Another study addressed landfill leachate treatment using a single-stage anoxic MBBR and aerobic membrane reactor, providing a detailed review of the previously investigated biological treatment technologies for greywater. This paper reported the biodegradability of the most popularly reported surfactant of each type (anionic, cationic, amphoteric, and nonionic surfactants) in domestic wastewater. The authors found that surfactants in greywater appeared to be highly biodegradable in most aerobic biological treatment technologies. Some studies have shown that anaerobic digestion processes can be inhibited due to the presence of surfactants, causing a decrease in methanogens activity. There are no stated mechanisms of inhibition that surfactants cause to anaerobic microorganisms. The design and operation of greywater biological treatment technologies should focus on the greywater characteristics, which can vary significantly contingent on the collection systems used. A comprehensive comparison between nutrient availability to biological treatment shows that dark greywater has a higher nutrient content than light greywater, especially nitrogen and phosphorus. We can improve the overall biodegradability of greywater under aerobic conditions by nutrient supplementation (Duyar et al., 2021).

Another study by the authors (Khalil M et al., 2021) showed the need to investigate combining moving bed and constructed wetland (MBCW) in terms of the removal capability. The study aimed to verify the availability using mixed bio carriers to analyze microbial community diversity and explain the removal mechanism of the bioreactor. This experiment used an innovative plexiglass-made cuboid integrated bioreactor with a total effective volume of 46 L. Different bio carriers were used in the bioreactor to provide a large surface for microbial attachment. Synthetic domestic wastewater was fed to the bioreactor according to the highly ammonified character of real domestic wastewater. A start-up period of twenty days was initiated to aggregate the biomass and form a biofilm on the bio carriers. The entire experiment took 360 days. The investigation results showed that the effect of the internal recycling rate (IRR), hydraulic retention time (HRT), and chemical oxygen demand/total nitrogen (C/N) ratio recommended values were 5:1, 12 h, and >6, respectively. A higher C/N ratio was a key factor for achieving a higher T.N. removal. The mixed bio carrier system was comprehended by inoculating Porous Polymer Carriers (PPC) and Cylindrical Polyethylene Carriers (CPC) and achieving a higher organic biodegradation and nitrification rate than a single carrier system. Results revealed an abundant microbial diversity and a distinct microbial distribution in the whole system where Flavobacterium (14.2%), Acinetobacter (12.87%), and Rhodobacter (10.83%) dominated on PPC, Terrimonas (8.88%), Reyranella (6.61%), and Rubinisphaera (5.63%) dominated on CPC, and Comamonas (4.18%), Gemmobacter (4.02%) and Hydrogenophaga (3.97%) dominated on constructed wetlands (CW), as well as Citrobacter (53.13%) on suspended floc (Khalil and Liu, 2021).

Ecological efficiency of the moving bed biofilm reactor (MBBR)

To serve the needs of developing countries and make the MBBR ecologically and economically self-sustainable, there was a need to focus on creating a compact, highly efficient, user-friendly, and cost-effective system incorporated with natural treatment. The author of the study (Yapıcıoğlu, 2019) explained the need for a package treatment plant for households to treat wastewater at the point of generation. Most package plants include biological unit operations as a secondary treatment to remove soluble pollutants (e.g., ASP, SBR, RBC, MBBR, SBBR, MBR) as well as wet composting and vermicomposting tanks anaerobic treatments; sand, soil, and peat filters; C.W.; and grey, black and urine water separation systems, following an initial primary treatment stage. The commercially available package treatment systems with high capital costs and energy-intensive operations are less sustainable in remote and rural areas. Although the efficiencies of commercially available package wastewater treatment systems are higher than CWs, desired effluent quality can be achieved. The effluent characteristics of C.W. are within limits given by authorities (Yapıcıoğlu, 2019). The author also studied the performance of a pilot-scale Integrated Settler Based Anaerobic Biofilm Reactor (ISBABR) and discussed the treatment of greywater generated from a hostel with the help of ISBABR. This research project was developed aiming for an electric-free, minimum capital cost, low operation, and maintenance-based onsite treatment system. The analytical results of this study showed that ISBABR is a very effective treatment system at the pilot scale for treating greywater with very low operation and maintenance costs, which shows its affordability and feasibility. According to the results, the removal efficiency of this system in terms of TSS, BOD, COD, orthophosphate, and ammoniacal nitrogen was 81%, 83%, 81%, 28%, and 23%, respectively. In the present ISBABR system, it was found that it had a much higher percentage of removal efficiency (Yapıcıoğlu, 2019).

A pilot-scale study is a feasible option for onsite domestic wastewater treatment for people living in developing countries in rural and semi-urban areas (Patil et al., 2021). The authors (Patil et al., 2021) recognized that hotels, residential buildings, industrial establishments, and institutions use a massive amount of water daily in baths, toilets, kitchens, and laundry. The authors wanted to check the possibility of using the Moving Bed Biofilm Process (MBBR) and a package sewage treatment plant for the total nutrient removal from municipal wastewater. The research methodology started with the working principle of the sewage treatment plant. It then moved to the unit operation and process of sewage disposal, which covers the physical, chemical, and biological unit operations. Next, the selection of sewage treatment technologies is described. Finally, the technological procedure for sewage treatment is reported. Data showed that waste stabilization ponds (oxidation ponds, maturation ponds, and duckweed ponds) are the best option for small towns that have land availability for treatment plants and a need for treated wastewater in agriculture. Also, there are some exemplary instances of treatment plants producing reasonably good quality water. This water is used in the industrial sector for processes and cooling purposes, thus reducing the industrial demand for freshwater (Singh et al., 2020).

One research team published an article that noted greywater reuse is rarely applied in Brazil. Water reuse is a fundamental approach and practice to reducing the pressures on water resources, lowering the demand for potable for purposes that do not require high-quality water. This study evaluated a greywater collection and treatment system from lavatories, showers, and washing machines aiming for non-potable reuse. It also characterized the quality and quantity of greywater from different sources to monitor a pilot system for synthetic greywater treatment and analyzed the effluent's quality after treatment. After evaluating the ability of a bioreactor (MBBR) to treat greywater produced in a staff building on a university campus, the findings showed that amongst the three greywater sources, the water from showers had the highest E. coli concentration. In contrast, the lavatories water had the highest total coliforms concentration. The removal efficiencies of BOD and COD were 59% and 70%, respectively. Results also showed that the phosphorus removal during the experimental period was low. The water quality produced is viable for outdoor purposes, landscape, and garden irrigation in households, as well as commercial and institutional buildings. The results were satisfactory according to Brazilian standards. The treatment showed stability and reliability, ensuring the potential for safe reuse if proper operation and monitoring of the treatment system is performed (Al Amimi et al., 2014).

However, the authors (Chrispim et al. 2017) found that only a few studies have discussed the ability of the (HMBBR) systems to remove micropollutants from wastewater. This study investigated the potential of a laboratory-scale HMBBR system, consisting of two bioreactors in series, to remove biological thiosulfate reduction (BTR), 4-methyl-1H-benzotriazole (4TTR), 4-methyl-1H-benzotriazole (5TTR), xylytriazole (XTR), chlorobenzotriazole (CBTR), and hydroxybenzothiazole OHBTH from domestic wastewater. A batch of experiments was conducted, and biodegradation kinetics was calculated. Aerated batch experiments were conducted by using biomass from BC1 where the greatest part of biodegradation was observed during the continuous flow experiment. According to Standard Methods, analysis of COD, NH4-N, NO3-N, Total Suspended Solids (TSS), and Mixed Liquor Suspended Solids (MLSS) was performed. The outcome was that the average removal of the target compounds ranged between 41% (4-methyl-1H-benzotriazole; 4TTR) and 88% (2-hydroxybenzothiazole; OHBTH) except for 4TTR; The degradation mainly occurred in the first bioreactor. The calculation of biodegradation constants in batch experiments showed that is mainly involved in the biodegradation of OHBTH, BTR, and XTR carriers. Both types contribute significantly to 4TTR biodegradation of biomass participate in the elimination of CBTR and 5TTR. Comparing the HMBBR system with MBBR or AS systems showed that the HMBBR system was more efficient for biodegradation. All the biotransformation products of target compounds were identified using ultra-high-performance liquid chromatography coupled with a quadrupole-time-of-flight high-resolution mass spectrometer (UHPLC-QToF-MS). Twenty-two biotransformation products were tentatively identified, while retention time denoted the formation of more polar transformation products than the parent compounds (Chrispim and Nolasco, 2017).

In research published in 2017, the authors showed evidence of the kinetics of organic matter degradation according to two types of sampling for understanding the role of each processing stage, especially in the removal of the organic matter, to optimize the system for future implementations. Twenty-four-hour composite samples were taken over ten days to determine the average removal of COD, DOC, and BOD7 in each reactor. Samples were used for the first-order kinetics study, during which the reactors were operated separately as batch reactors on different days. Fresh greywater was entered into the system to obtain high initial BOD and COD concentrations. No greywater was pumped into the system during sampling so that the individual reactors were operated as batch reactors for 6 hours. Hourly samples were taken and analyzed directly. Results showed that the reduction of the organic matter was reached in the first three reactors, while the highest reduction rate was observed in the third reactor in terms of COD, DOC, and BOD7. The average rate of loading entering the system was 3.7 kg COD/d, while the average rate of removal was 3.4 kg COD/d in a total bioreactor volume of 11.7 m^3. The BOD was 2.8 kg BOD/d, and it was almost completely removed. This system requires little space of average (0.15 m^2/person) and average maintenance of less than one hour per month, and it has operational stability under peak loads (Mazioti et al., 2017).

A study by (Jabri K et al., 2019) stated that the demand for fresh water in a growing population is essential for water resource sustainability. The dairy industry wastewater treatment plants are a major polluter due to the large wastewater discharges and the high organic content. A methodology of comparing four treatment scenarios, including no treatment process, was used in this study. The Water Footprint Network (WFN) method was used for the greywater footprint (GWF) assessment by taking into consideration three pollutant parameters: fats, COD, grease (FOG), oil, and TSS. In Scenario-1, the primary treatment uses Dissolved Air Flotation (DAF). In Scenario-2, the secondary treatment uses DAF and an Up-flow Sludge Bed (UASB) reactor. In Scenario-3, a DAF and UASB use a reuse application applying reverse osmosis (RO). Finally, Scenario-4 has been studied for a full-scale dairy industry wastewater treatment plant. The results show that the GWF in Scenario-4 for COD was the lowest, with a value of 5,609 m3/d. Scenario-1 has the highest GWF for TSS with a value of 41,026 m3/d. Based on the assessment results, reuse applications decrease the GWF values. It was also shown that it is possible to reduce the GWF using reuse processes in a dairy Wastewater Treatment Plant (WWTP). A reduction of up to 38% has been observed by combining the existing treatment method with an R.O. process. Reuse applications can minimize the GWF (Jabri et al., 2019).

In a study conducted in Greece, the authors (K.J. S et al., 2020) focused on the vertical flow constructed wetland (VFCW) use for vegetation of greywater treatment vs. ornamental plants. The experiment took place at the outdoor research facility of The University of the Aegean in Mytilene, Greece. Influents and effluents were sampled weekly for approximately 3 months. The samples were analyzed and tested for TSS, electrical conductivity (E.C.), pH, BOD, COD, and total phosphorus (T.P.). The results showed that the proposed "treatment gardens" provide a feasible solution, technically and economically for greywater treatment (GWT), with the additional benefit of improving the aesthetic quality of urban, semi-urban, and touristic areas. High average removal efficiencies were observed for BOD (99%), COD (96%), and TSS (94%) in all examined VFCWs, including unplanted beds.

Phosphorus removal gradually decreased from 100% during the first months of operation to 15% during the second year of operation. Total coliforms concentration was reduced by 2.2 units log in the effluent of all planted systems, while lower efficiency of removal was observed in the absence of plants. The mean concentration of BOD and TSS in the treated greywater met the standards for indoor reuse (b10 mg/L). Pittosporum tobira and Hedera helix can grow in VFCW operating with greywater use without any visible symptoms (KJ and PA, 2020).

A paper titled "Use of Ornamental Plants for Greywater Treatment" proposed MBBR as a novel technology that contributes to the wastewater treatment (WWT) circularity sector according to the fundamentals of the circular economy. The authors aimed to consider the Moving Bed Biofilm Reactor MBBR process as the initial step for water reuse and removal of nutrients and recovery within the circular economy model. This paper found that many studies have proven that MBBR and MBBRMBR systems are suitable technologies to produce high-quality reclaimed wastewater. Both nutrient recovery and treated wastewater reuse could help the transition to a circular economy model by reducing the consumption of virgin resources (Kotsia et al., 2020).

However, the authors Leyva-Díaz J et al., 2020, noticed the impact of the exposure of 17β-estradiol (E2) that humans and animals secrete through excreta; it is widely encountered in aquatic environments. As the primary and most potent form of natural estrogen, known to cause adverse impacts on reproductive systems of aquatic animals, the concentration is commonly reduced to the ng/L level. This study investigated the relation between nitrification and 17β-estradiol (E2) degradation in synthetic maricultural wastewater by ammonia-oxidizing bacterium Nitrosomonas Europaea and MBBR. Experiments were designed to address the following two topics about E2 removal performance by N. europaea and by MBBR: the impacts of E2 on bacterial density and AMO enzyme activity of N. europaea and the impacts of E2 on the biological performance of MBBR. The results provided comprehensive information for understanding the E2 biodegradation behavior during the aerobic nitrification process. The results showed that E2 interfered with the ammoxidation process of both pure N. Europaea and MBBR, but it was efficiently removed in this process. Reducing E2 down to 50 ng/L could significantly reduce the nitrite yield, bacterial density, and AMO activity of N. Europaea. In contrast, ammoxidation slowed down in the MBBR when inlet E2 increased from 10 μg/L to 1 mg/L (p b.05), which was likely ascribed to the significant role of abundant heterotrophs apart from AOB. Surprisingly, accelerated E2 removal occurred at a dosage of 1 mg/L compared to that of 10 μg/L by the MBBR (p b.05). Nitrite oxidation was not affected upon E2 exposure regardless of the E2 concentration (Leyva-Díaz et al., 2020).

Another study (Li et al., 2020) evaluated the treatment of synthetic greywater by a bench-scale O2-MBR. The authors investigated how to feed loading affects organics and nitrogen removal and how it impacts the effluent dissolved oxygen (DO) concentration in the MBR. Further, this study assessed the role feed loading might play in the microbial community dynamics in the biofilm to lay the foundation of process optimization and cost-cutting for the practical application of O2-MBfR for greywater treatment. Results showed that The MBfR successfully achieved simultaneous organics and nitrogen reduction, with overall average removal ratios of 98% for linear alkylbenzene sulfonates (LAS), 95% for total chemical oxygen demand (TCOD), and 99% for inorganic nitrogen (InON). Also, it showed that increasing feed loading rates led to the gradual decrease of dissolved oxygen (D.O.) concentration from 1.67 to 0.37 mg/L in the reactor and induced the formation of complex biofilm containing aerobic-anoxic, aerobic-anoxic-anaerobic, and distinct aerobic layers. All these contributed to the simultaneous removal of both nitrogen and organics in MBR. Mechanisms of nitrogen and organics removal included aerobic denitrification and nitrification in partial nitrification in the aerobic-anoxic biofilm, aerobic biofilm, and partial nitrification and anaerobic denitrification in the aerobic anoxic-anaerobic biofilm due to the co-existence of various functional microorganisms in the O2-MBfR (Li et al., 2020).

Meanwhile, (Zhou Y et al., 2020) studied the coupling of the conventional single stage with Moving Bed Biofilm Reactor and membrane bioreactor (AnoxMBBR/AeMBR) for Landfill leachate (LFL) treatment. This paper investigated the pollutants removal efficiency and the operational stability of single-stage AnoxMBBR and AeMBR under varying nitrate concentrations (100–1000 mgNO3 −-N/L), SRT (30–90 d), and HRT (24–48 h) in the anoxic zones. A laboratory-scale AnoxMBBR-AeMBR was constructed and continuously operated for 223 days to evaluate the long-term performance of AnoxMBBR-AeMBR in terms of COD, NH4 +-N, NO3 −\\N, heavy metals, biofilm structure, and properties, permeate flux, and membrane fouling, to understand the removal mechanisms in AnoxMBBR-AeMBR and to determine the diversity of the microbial community in AnoxMBBRAeMBR by high throughput next-generation sequencing analysis. The results confirmed that the anticipated sequence is efficient for COD removal, nitrogen removal, and PAEs, therefore making it an acceptable treatment for landfill leachates. The best system performances were detected at SRT of 90 d, and HRT of 48 h, 1000 mgNO3−-N/L concentration and the average removal efficiencies of chemical oxygen demand (COD), ammonia nitrogen (NH4+-N), and nitrate-nitrogen (NO3 −\\N) were 74.2%, 99.7%, and 89.1%, respectively. Consequently, the AeMBR was achieved above 99% NH4. A slight increase in di (2-Ethylhexyl) phthalate (DEHP), selected phthalic acid ester (PAE) concentrations (diethyl phthalate (DEP), diisononyl phthalate (DINP)) was detected in the AnoxMBR, and complete PAEs removal was attained in the AeMBR. Mg, Al, Si, Na, and Fe were detected by SEM-EDX analyses in both the biofilm of AnoxMBBR and the cake layers of AeMBR. Nitratireductor and Nitrobacter, which showed a relatively high abundance, played an important role in removing NH4 +-N and COD in LFL+-N removal and were not adversely affected by varying operation conditions AnoxMBBR (Zhou et al., 2020).

Economic applications of the moving bed biofilm reactor (MBBR)

The economic feasibility of decentralized wastewater treatment systems is a crucial factor in its application. One paper studied the stage-by-stage design for primary, conventional activated sludge, SBR, and MBBR units for residential wastewater treatment and reuse. The study focused on the feasibility of improving the biodegradability by pretreating the effluent using namely homogeneous solar photo-Fenton (HSPF), advanced oxidation processes, and advanced solar photo-Fenton (ASPF) processes and subsequent treatment through the (MBBR) exposed with a magnetic field. The response surface methodology (RSM) was applied as a tool to optimize the operational parameters of inhomogeneous solar photo-Fenton (HSPF), ASPF, and MBBR processes. Box–Behnken Design (BBD) to optimize the response requires few runs to make its application more economical. NaOH or H2SO4 was used to adjust the pH of the wastewater. A bioassay test was used to assess the toxicity of the effluent. Testing was performed at room temperature using Poecilia liberties reticulate (Guppy fish) as the test organism. An acrylic glass reactor of 11.25 L capacity was employed for the MBBR experiment. The results showed biodegradability enhancement after pretreatments were confirmed by the B.I., kinetic coefficients, and toxicity test. An improved volume of sludge index of the pretreated effluents ensured the satisfactory physical state of the sludge. When inducing the magnetic field to the treated MBBR, it was found that the effluents after pretreatments were disposed of either into irrigation water or into inland waters, conforming to the standards of effluent parameters. Also, it was found that the carrier materials inoculated with predominant bacteria present in the textile sludge identified by the 16S rRNA method have been used in the MBBR. Box–Behnken Design (BBD) in response surface methodology was used to optimize the photo-Fenton and MBBR treatment parameters. The ASPF–MBBR integrated process has proved slightly less expensive when compared to the cost of the two integrated processes (MBBR + HSPF and ASPF + MBBR) (Aziz et al., 2020).

(Daude and Stephenson, 2004) found that MBBR small-scale plant was designed to provide a compact and cost-effective treatment solution for rural households in India. Over eight months, such a small plant was operated under normal conditions and subjected to different shock scenarios to evaluate its suitability for small-scale sewage treatment systems. The authors conclude that effective sewage treatment combined with simple and reliable operation proved that MBBR technology is a viable solution for small-scale applications.

Overall, there is a lack of studies that assess the economic and life cycle implications of small scale for residential and commercial applications. There is a need to carry out pilot studies at various small-scale settings to assess the limitations such as the high initial and operational costs and returns to investment in small-scale MBBR technology.

CONCLUSIONS

Technical efficiency

The technical efficiency discusses the different treatment systems which are described in the analyzed papers and studies included in this review study. The Integrated Settler Based Anaerobic Biofilm Reactor (ISBABR) was constructed based on the design of a laboratory-scale reactor resulting in a Total Suspended Solids (TSS), Biological Oxygen Demand (BOD), and COD of 81%, 83%, and 81% removal efficiency respectively. Sewage treatment plants and MBBR technology provide efficient sewage treatment alternatives. The removal efficiency of the biocides varied from 87% to 99%, which is greater than the composite parameters' removal efficiencies. The main removal mechanisms are settling and adsorption. For low, medium, and high influent concentrations, Total Suspended Solids (TSS) removal efficiency was 83.6%, 92.8%, and 94.8%, respectively. For the MBBMR, COD removal efficiency was 70%, TSS removal was 97%, and turbidity removal was 98%. Bacteria were found in high concentrations in 60% of the reclaimed wastewater samples, exceeding the local and widely accepted standards internationally. The BOD and COD removal efficiencies were 59% and 70%, respectively. The HMBBR system was found to be more efficient for biodegradation. The organic substrate removal performance of the multistage greywater treatment system was optimal, with COD, BOD, and DOC reductions of 94%, 99%, and 91%, respectively. Hybrid technologies were determined to be the most promising methods for the nearly total removal of contaminants from wastewater.

MBRs have been found as a successful general technique for greywater treatment. The reverse osmosis (R.O.) procedure has the lowest Grey Water Footprint (GWF) for three pollutant metrics. The SBR and MBBR methods are more efficient than the Conventional Activated Sludge (CAS) approach. In the ornamental plants for greywater treatment, Phosphorus elimination declined significantly from 100% during the first months of operation to 15% during the second year. Conventional wastewater treatment plants can never be revenue-generating. The operational issues and high expenses are the two most significant downsides of a multiple-stage system.

Ecological and economic efficiency

The ecological, commercialization and economic impact for different treatment systems that are described in the analyzed papers and studies are summarized in the following points: nutrients, inorganic salts, pathogens, coarse particulates, and other contaminants and wastes are found in wastewater, all of which are harmful to the environment and humans. The commercially available package systems in the market are energy-intensive and have high capital costs. Moving Bed Biofilm Reactor (MBBR) is efficient when a bacterial analysis is considered compared to other alternative systems. The most cost-effective and practical method for greywater recycling is a combination of aerobic biological processes, physical filtering, and disinfection. Recycling water is not recommended for agricultural purposes because of concerns regarding health and environmental threats. Greywater reuse has the potential to reduce urban wastewater discharge while also improving environmental health by lowering energy consumption and water and land pollutants. Decentralized source separation is a low-cost, ecologically friendly technique that is ideal for rural locations. Most DWTS use gravity flow rather than pumping, which reduces the cost and energy requirement while still allowing the system to be small enough to fit into tiny settlements. Greywater reuse has environmental and economic benefits; however, these benefits are not without risk. The use of freshwater resources due to a growing population has resulted in water shortages. Reusing treated wastewater for agriculture irrigation is very necessary and cheaper than using potable water from drinkable groundwater wells. The payback time for single residences is predicted to decrease to 7 years. Treatment of urban wastewater has been viewed to limit pollutant emissions into the environment while also preventing pollution of receiving water bodies. Increased feed loading resulted in a significant reduction in D.O. in both the biofilm and the effluent. Combining MBBRs and C.W.s is seen as a potential and alternate solution for future advances in domestic wastewater treatment. The BMW hybrid system provided a cost-effective and efficient solution for installing or upgrading WWTPs.

In brief, MBR and MBBR wastewater treatment systems represent efficient and environmentally effective processes that cope excellently with the increasing need for transforming wastewater into clean greywater that can be reused for irrigating homes or office gardens. Information regarding technical, ecological, and economic efficiency showed that the application of the Moving Bed Biofilm Reactor (MBBR) system for domestic use is technically and ecologically sound and more efficient when compared to Membrane Bioreactor (MBR) and Submerged Aerobic Fix Film (SAFF). However, previous studies and personal communications by authors of this study indicated the initial capital cost of MBR and MBBR wastewater treatment is high for small and medium-size domestic applications. Expanding the use of the system for domestic use may increase its economy of scale and so reduce the initial capital cost for small and medium domestic applications worldwide (e.g., homes gardening, sanitation, commercial, and landfills) (Gurjar et al., 2019).

Authors contributions

The authors in this study equally contribute to the concept, literature review, analysis, writing, and editing of the manuscript.

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