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Treatment of Textile Wastewater by CAS, MBR, and MBBR: A Comparative Study from Technical, Economic, and Environmental Perspectives

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Abstract: In this study, three different biological methods—a conventional activated sludge (CAS) system, membrane bioreactor (MBR), and moving bed biofilm reactor (MBBR)—were investigated to treat textile wastewater from a local industry. The results showed that technically, MBR was the most efficient technology, of which the chemical oxygen demand (COD), total suspended solids (TSS), and color removal efficiency were 91%, 99.4%, and 80%, respectively, with a hydraulic retention time (HRT) of 1.3 days. MBBR, on the other hand, had a similar COD removal performance compared with CAS (82% vs. 83%) with halved HRT (1 day vs. 2 days) and 73% of TSS removed, while CAS had 66%. Economically, MBBR was a more attractive option for an industrial-scale plant since it saved 68.4% of the capital expenditures (CAPEX) and had the same operational expenditures (OPEX) as MBR. The MBBR system also had lower environmental impacts compared with CAS and MBR processes in the life cycle assessment (LCA) study, since it reduced the consumption of electricity and decolorizing agent with respect to CAS. According to the results of economic and LCA analyses, the water treated by the MBBR system was reused to make new dyeings because water reuse in the textile industry, which is a large water consumer, could achieve environmental and economic benefits. The quality of new dyed fabrics was within the acceptable limits of the textile industry.

Keywords: membrane bioreactor (MBR); moving bed biofilm reactor (MBBR); conventional activated sludge system (CAS); textile wastewater; economic feasibility; life cycle assessment (LCA); water reuse

1. Introduction

As one of the largest industries worldwide, the textile industry produces significant amounts of wastewater. Textile wastewater is generated in different steps during production, such as destarching, mercerization, dyeing, and washing [1], and is known to contain considerable amounts of organic compounds which provide color to the effluent [2]. In recent years, more strict regulations of effluent discharge have been applied in the textile industry, in order to reduce dye residues in the effluent before discharge into natural streams [3]. Consequently, finding suitable technologies to obtain an effective treatment of textile wastewater and to reuse its effluent in new production processes is essential for the industry's sustainable development.

One of the most applied biological methods in treating textile wastewater is the conventional activated sludge (CAS) process [4,5]. The main objective of the CAS process is to remove organic compounds [6]. The CAS system has disadvantages such as high hydraulic retention time (HRT), problems with sludge settling, requirement of large space [7], and poor color removal efficiency due to the low biodegradability of dyes which can only be partially adsorbed on biomass [8–10]. Hence, a tertiary physicochemical method is usually required to give a better treatment performance [3,11], which will increase the cost of the process.

In the past two decades, noticeable progress has been achieved with membrane bioreactor (MBR) technology in industrial wastewater treatment. MBRs separate the sludge by filtration, which differs from conventional CAS treatment [12]. MBRs can reduce land space and sludge production with a high biomass concentration in the reactor and are able to treat influent with wide fluctuations of quality [13–16]. In the case study of MBR applied in textile wastewater treatment in Bangladesh, the performance of the MBR system was better than that of the CAS [17]. Another study reported that high removal efficiencies were achieved for chemical oxygen demand (COD), color, and total suspended solids (TSS), and the cytotoxicity was significantly reduced by MBR when operating at an HRT of 2 days [18].

Recently, biofilm systems have drawn much attention in treating different types of industrial wastewater due to their several advantages compared with conventional biological treatment, including saving space [19,20]. Among them, the moving bed biofilm reactor (MBBR) also has been applied in textile wastewater treatment in the last few years. One of the highlights of MBBR is a smaller volume of the biological plant or a larger treating capacity in the same reactor volume due to the biofilm being attached to carriers. Besides the great amount of biomass fixed on carriers, the concentration of biomass in suspension could be higher than that in the CAS process. In a previous study of textile effluent treatment [21], the pilot-scale plant of MBBR removed 86% of COD and 50% of color, respectively.

In addition to the selection of suitable wastewater treatment from a technical point of view, the increased demand for sustainability of industries has led to the use of life cycle assessment (LCA) as a tool to evaluate the feasibility of technologies [22]. Previous studies have estimated the environmental impacts generated by one or combined units of treatment plants for textile wastewater. Nakhate et al. evaluated the environmental footprints of a textile wastewater treatment plant and found out that consumption of electricity dominated in most of the environmental burden [23]. Cetinkaya and Bilgili compared, in another study, the environmental impacts caused by two desalination systems, and they found that using LCA could assess the environmentally friendlier treatment system for textile wastewater [24].

The aim of the current experimental study was to compare the efficiency of the CAS system, MBR process, and MBBR system in treating real textile wastewater. CAS is the current treatment process of the textile industry which provides the wastewater for our study. In order to improve the treating efficiency based on the existing CAS treatment, we have chosen MBBR and MBR to compare the technical, environmental, and economic feasibility. Parameters such as chemical oxygen demand (COD), total suspended solids (TSS), and color were determined to verify that MBR and MBBR have a better efficiency than CAS process. Special attention was paid to color removal, as color is one of the main problems in textile wastewater treatment.

Based on the experimental results in the pilot plant, an economic study and LCA were carried out to compare the economic and environmental feasibility of implementation of these technologies on an industrial scale and also to select the method of textile wastewater treatment with lower investment, operating costs, and environmental impact related to energy and materials consumption.

Water treated with the most viable method was reused to make new dyes because water reuse in the textile industry, a large water consumer, is one of the main factors to achieve sustainable development.

2. Methodology

2.1. Pilot Plant Description and Analysis

Three pilot plants (flow diagram shown in Figure 1) were investigated for textile wastewater treatment in this study. Among them, the plant for the CAS process and the plant for MBR were operated in parallel. The pilot plant for MBBR was the same as for the CAS operation, but without the recirculation of sludge. The three treatments were operated with a controlled temperature of 25 °C.

The textile wastewater was obtained from a local textile industry, Acabats del Bages, S.A. (Monistrol de Montserrat, Spain). The characteristics of the wastewater are shown in Table 1, including pH, COD, color, biochemical oxygen demand (BOD), TSS, total nitrogen (TN), and total phosphorous (TP). The duration of experiments for three pilot plants was 96 days.

It should be noted that the pH of wastewater returned to 8.6 in the reactor due to the buffering effect caused by the presence of carbonates, usual in textile wastewater. It was unnecessary and unattainable on an industrial scale to adjust the pH. Therefore, in the economic and LCA study, we did not take into account the amount of acid on the industrial scale.

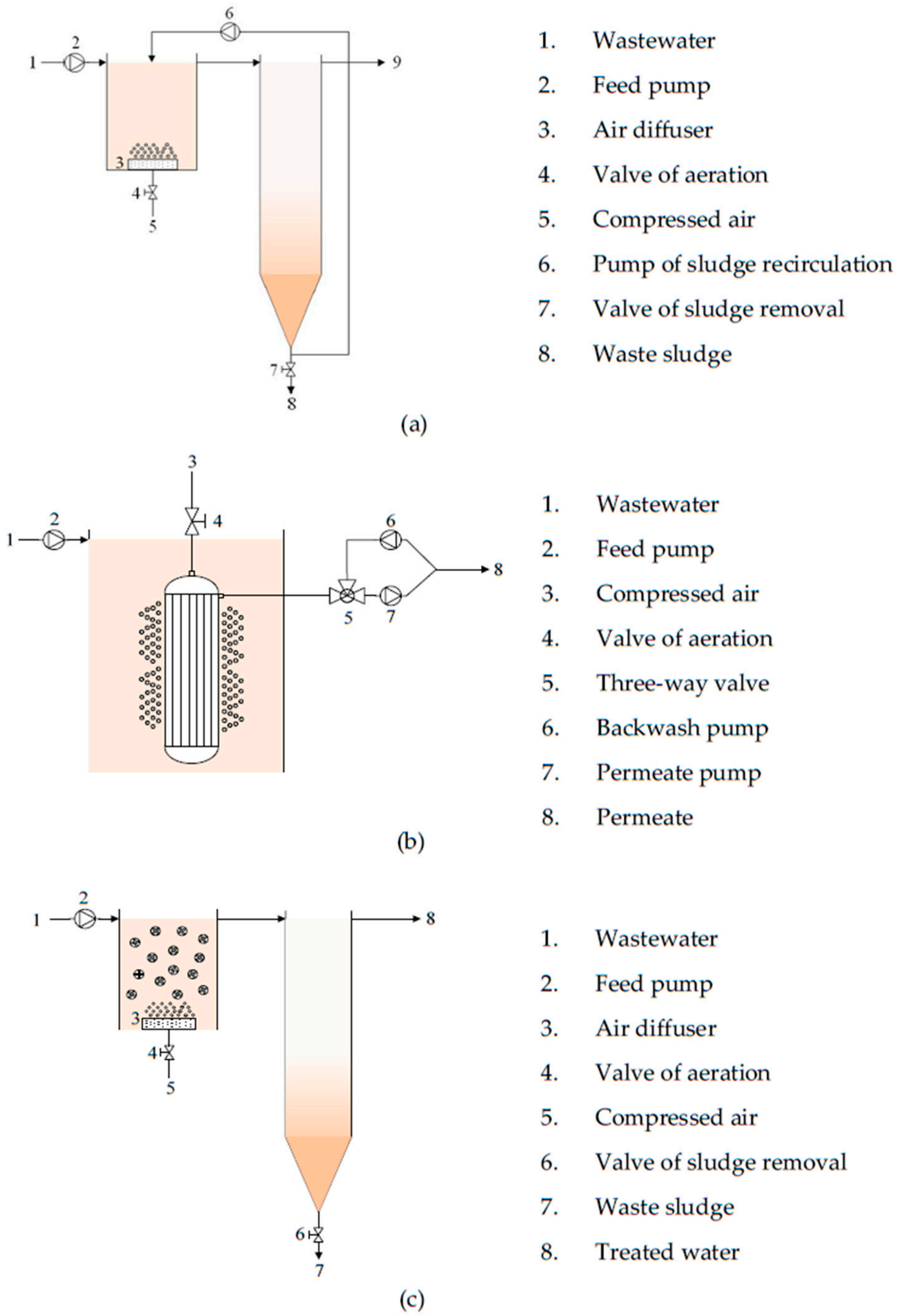


Figure 1. Flow diagrams of (**a**) conventional activated sludge (CAS); (**b**) membrane bioreactor (MBR); (**c**) moving bed biofilm reactor (MBBR).

Table 1. Characteristics of textile wastewater.

Parameters	Average
pH	8.6 *
COD mg/L	2000
Color Pt-co /L	700
BOD mg/L	400
TSS mg/L	940
TN mg/L	54
TP mg/L	11

* The pH of the original textile wastewater was initially adjusted from 8.6 to 7.2 before the treatments. COD: chemical oxygen demand; BOD: biochemical oxygen demand; TSS: total suspended solids; TN: total nitrogen; TP: total phosphorous.

The CAS pilot plant was composed of an aerobic reactor (volume 4 L) connected to a decantation tank. The flow rate in the CAS plant was 2 L/d, and the HRT was set to 2 days as the HRT of the current CAS plant of the textile industry.

The MBR used in this study was a pilot plant, composed of an aerobic reactor with a submerged ultrafiltration membrane. A Polyvinylidene fluoride (PVDF) hollow fiber membrane module ZeeWeed-1 (ZW-1) (GE Power & Water, Canada) was used. The membrane characteristics are shown in Table 2. The aerobic reactor had a working volume of 20 L. The influent was pumped directly from a raw wastewater tank, mixed completely with aeration in the reactor. There was an air inlet in the membrane module to prevent membrane fouling. The period of filtration and backwashing was set at 15 min and 30 s for the laboratory-scale reactor according to previous study with the membrane module [25].

Table 2. ZeeWeed-1 (ZW-1) membrane characteristics.

Model	ZW-1, submersible module
Configuration	Outside/in hollow fiber
Membrane Surface	0.05 m^2
Pore Size	0.04 µm
Maximum Transmembrane Pressure (TMP)	0.62 bar
Typical Operating TMP	0.1–0.5 bar
Maximum TMP Backwash	0.55 bar
Operating pH Range	5–9

As mentioned before, the MBBR pilot plant was the same one as in the CAS process. The aerobic reactor was filled with the carriers at a filling ratio of 30% (v/v). The plastic BIOFILL C-2 carriers used in this study were provided by BIO-FIL (Barcelona, Spain). The main specifications and operation characteristics of carriers are shown in Table 3. MBBR operation was inoculated with aerobic sludge collected from the wastewater treatment plant of the same textile industry. The start-up period lasted 3 weeks so biofilm could grow on the carriers.

Table 3. BIOFILL type C-2 carrier characteristics.

Specific Surface	590 m^2/m^3
Piece Diameter	25 mm
Free Volume	90%
Weight per Piece	2.1 g
Density	<1 kg/m^3

In the initial phase, both MBR and MBBR were operated with 2 days of HRT, as was the CAS system. In order to assess a larger treating capacity and efficiency, the flow rate was increased gradually during the experiments. The flow rate in the MBR plant was fixed at 15 L/d and the HRT was 1.3 days, whereas the flow rate in the MBBR plant was 4 L/d and the HRT was fixed at 1 day. In the phase after the flow rates were stable, the concentration of dissolved oxygen (DO) in CAS was 2.1 mg/L, similar to the DO level in the MBBR reactor of 2.2 mg/L. MBR had a lower DO concentration of 1.8 mg/L.

2.2. Economic Analysis

The economic assessment of capital expenditures (CAPEX) and operational expenditures (OPEX) for three treatment schemes is determined in the results section.

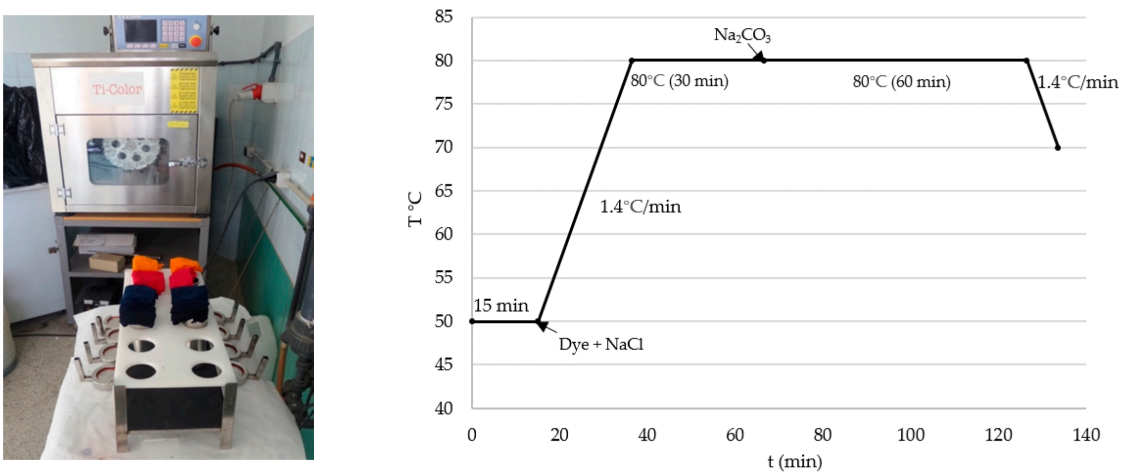
2.3. Environmental Impact Analysis

To compare the environmental impact of three treatment processes, life cycle assessment (LCA) was performed according to standard ISO 14040 [26]. Simapro was used as the LCA software. The database used was Ecoinvent 3.1. ReCiPe, midpoint and endpoint approach, and Hierarchist perspective were considered as the methodology to calculate environmental impact. The selected functional unit was "1 m^3 of treated effluent". The data used in this study were taken from the experimental results.

2.4. Dyeing Tests Using Treated Water

The dyeing tests using treated water were performed with a laboratory Ti-Color dyeing machine (Prato, Italy) (Figure 2a) under the following conditions [27]: 10 g cotton fabric, dye concentration of 3% o.w.f (overweight of fiber), liquor ratio 1:10 (1 g fiber/0.01 L dye bath). Three commercial reactive dyes supplied by Dystar were used in the water reuse study: Yellow Procion HEXL, Crimson Procion HEXL, and Navy Procion HEXL. Besides the amount of dye, 60 g/L NaCl and 26 g/L Na_2CO_3 were added. The dyeing procedure is shown in Figure 2b. After the dyeing procedure, nine washing steps were performed with softened tap water to remove the dye that was not fixed onto the fiber. This washing process included nine steps:

- 1st–3rd: Washing bath with softened tap water at 50 °C for 10 min;
- 4th: Soaping bath with 2 g/LCOTEMOLL TLTR at 95 °C for 15 min;
- 5th: Rinsing bath with softened tap water at 50 °C for 10 min;
- 6th: Soaping bath with 2 g/L COTEMOLL TLTR at 95 °C for 15 min;
- 7th–9th: Rinsing bath with softened tap water at 50 °C for 10 min.



(**a**) (**b**)

Figure 2. (**a**) Ti-Color equipment (**b**) dyeing procedure.

2.5. Analytical Methods

During this study, the control of the three pilot plants was carried out with analyses by characterizing the water at the entrance, in the bioreactor, and at the exit to determine the working efficiency. COD, TSS, TN, TP, color, pH, conductivity, and turbidity were determined following the Standard Methods 23rd edition [20].

The quality of dyed fabrics with reused water was determined according to Standard UNE-EN ISO 105-J03 by color differences with respect to reference dyeings performed with softened tap water [28]. Total color differences ($DE_{CMC(2:1)}$) were calculated from lightness (DL*), chroma (DC*), and Hue (DH*) using the following equation:

$$DE_{CMC(2:1)} = \left[\left(DL \cdot S_L \right)^2 + \left(DC^*_{ab} / S_C \right)^2 + \left(DH^*_{ab} / S_H \right)^2 \right]^{1/2} \quad (1)$$

where S_L, $S_{C,}$ and S_H were calculated from the chromatic coordinates corresponding to reference dyeings (L_R, $C_{R,}$ and h_R) as follows:

$$S_L = 0.040975L_R/(1 + 0.01765L_R) \quad (2)$$

$$\text{If } L_R < 16, S_L = 0.511 \quad (3)$$

$$S_C = [0.0638C_R/(1 + 0.0131C_R)] + 0.638 \quad (4)$$

$$S_H = S_C(T_f + 1 - f) \quad (5)$$

$$f = \{(C_R)^4/[(C_R)^4 + 1900]\}^{1/2} \quad (6)$$

$$T = 0.36 + |0.4 \cdot \cos(35 + h_R)| \text{ if } h_R \geq 345^\circ \text{ or } h_R \leq 164^\circ \quad (7)$$

$$T = 0.56 + |0.2 \cdot \cos(168 + h_R)| \text{ if } 164^\circ < h_R < 345^\circ \quad (8)$$

A spectrophotometer, MINOLTA CM 3600d (Osaka, Japan), was used for these measurements according to Standard illuminant D65/10°.

Generally, the color difference of one unit ($DE_{CMC\,(2:1)} \leq 1$) is the acceptable limit in the textile industry.

3. Results and Discussion

3.1. Treating Efficiency

During the experiments, the average biomass concentrations in the reactor of CAS, MBR, and MBBR were 3 g/L, 2.3 g/L, and 3.5 g/L, respectively. As the textile wastewater had rather low contents of TN (54 mg/L) and TP (11 mg/L), over 90% removal of TN and TP was obtained after MBR and MBBR treatment, whereas CAS eliminated 88% of TN and TP.

As mentioned in Section 2.1, the initial HRT for CAS, MBR, and MBBR was 2 days, whereas the initial organic loading rate (OLR) was the same for the three treatments at 1 kg COD/ (m^3 d). The HRT of MBR and MBBR was gradually reduced to evaluate if the treating efficiency could be maintained while the treating capacity was increased.

Color in the influent varied between 400 and 1500 mg Pt-co/L. The removal rates of color obtained by the three treatment systems are shown in Figure 3a. The average color removal efficiency was 55% in the CAS process and was 80% in the MBR system, while in the MBBR system the color removal achieved 61%. MBR was significantly more efficient at removing color than the CAS process under the same operating conditions. MBBR had a higher color-removing performance than the CAS process, while the HRT (2 days) of CAS was twice the HRT (1 day) of MBBR. In order to meet discharge standards, decolorizing agent was added to the effluent from the CAS and MBBR processes. After adding 200 ppm of decolorizing agent, the color content reached the discharge standard in CAS, while the amount of decolorizing agent needed for MBBR was 100 ppm. In conventional biological treatment, the addition of various adsorbents and chemicals into the activated sludge system to improve the color removal efficiency is a common method, which will increase the cost and will generate secondary contaminates [29,30].

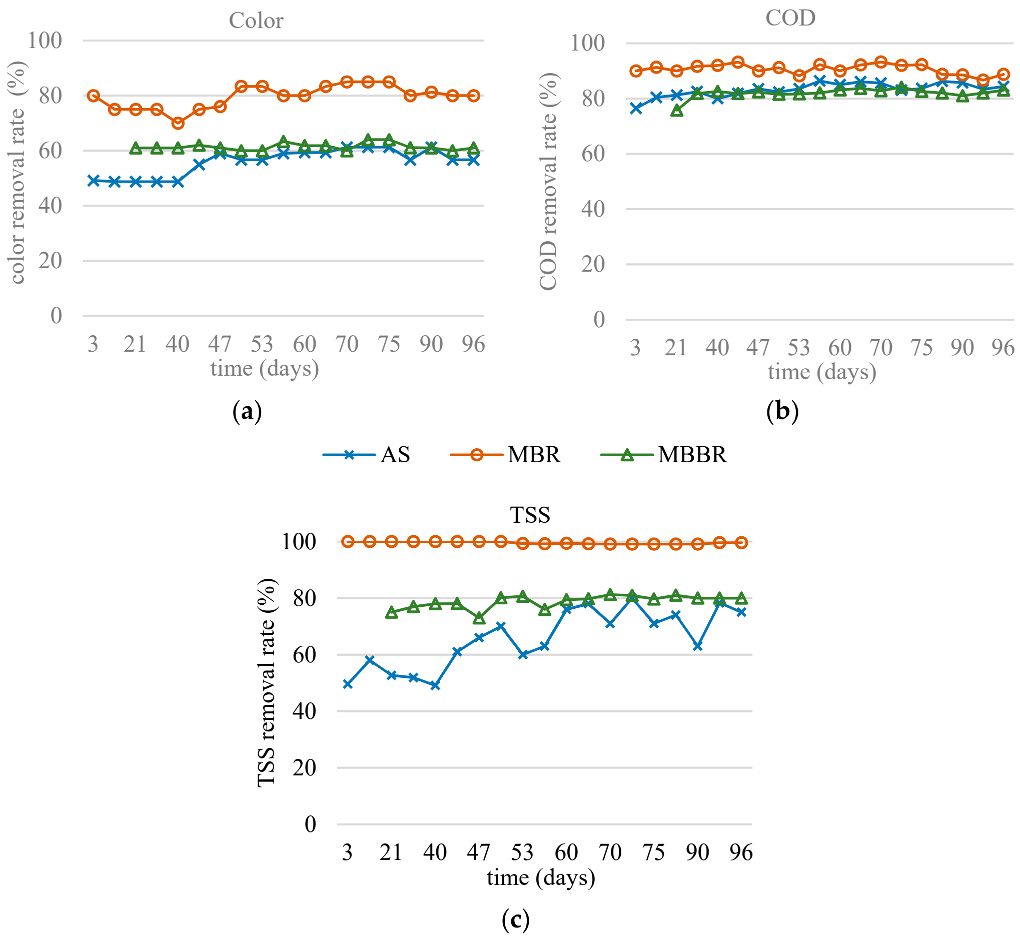


Figure 3. Removal rates of color (**a**), COD (**b**), and TSS (**c**) in activated sludge system, MBR, and MBBR.

COD of the influent remained at about 2000 mg/L. The average COD effluent of the CAS process was 350 mg/L, and the average efficiency of COD removal was 83%. The average COD value of the effluent from MBR was 170 mg/L, and the COD removal rate was 91%. The removal rates of COD in the three pilot plants are illustrated in Figure 3b. Furthermore, the CAS process worked with an HRT of 2 days, while the HRT of MBR worked only within 1.3 days. This demonstrated the efficiency and stability of the biological process of MBR. Similar results of COD removal in the MBR system and CAS process were also observed previously [17,31], indicating that after MBR treatment, a better COD removal efficiency can be obtained from the conventional AS process. The average COD value of the effluent from MBBR was 179 mg/L, and the COD removal rate was 82%. Although the removal rates of COD of the CAS and MBBR processes were similar, HRT of MBBR was half of the HRT of the CAS process. The average OLRs for the CAS system, MBR, and MBBR were 1 kg COD/ (m^3 d), 1.5 kg COD/ (m^3 d), and 2 kg COD/ (m^3 d), respectively.

The TSS removal rates in the CAS system, MBR, and MBBRs are shown in Figure 3c. During the parallel experiments of CAS and MBR systems, the average value of TSS in the influent was 940 mg/L. The average TSS removal efficiency in the CAS process was 66%, while in MBR system the TSS removal achieved 99.6%. From the perspective of TSS removal, membrane filtration is an attractive method because of the total retention of suspended matter and significant retention of colloidal matter [32]. The results showed the advantage of the MBR process in TSS reduction with respect to the CAS process.

The MBR process reached high TSS elimination without the necessity to add a tertiary treatment. MBBR achieved an average TSS removal rate of 78%, which was better than that of the CAS system.

3.2. Economic Study of the Three Treatment Processes

The local textile industry produced 222,700 m^3 of wastewater per year with 11 months under operation. The wastewater treatment method of the industry is conventional activated sludge (CAS). The daily treatment flow is 920 m^3/d. The current HRT of the CAS plant is 2 days.

3.2.1. Capital Expenditures (CAPEX)

The CAPEX of the CAS system was considered to be the reference (0) in the economic study. The CAPEX of MBR and MBBR treatments were added directly to the CAPEX of the CAS system.

For the MBR full-scale system, the membrane and the installation of the membrane (366,153 €) have been considered for the CAPEX estimation according to the CAPEX calculation from a study of the cost of a small MBR (100–2500 m^3/d flow capacity) [33].

For the MBBR full-scale system, the cost of carrier medias (115,500 €) has been considered for the CAPEX estimation according to the suppliers' information.

3.2.2. Operational Expenditures (OPEX)

Consumption of energy, decolorizing agent data, and environmental tax of sludge production and wastewater discharge were gathered in order to estimate operational expenditures (OPEX) of the three treatment plants.

Additionally, the cost of membrane replacement represented 2.4% of the energy cost [34], and the average lifetime of the UF membrane was taken as 10 years. The maintenance and repair costs represented 19.5% of the energy cost [34]. MBR could withstand higher concentrations of biomass with much longer sludge retention time (SRT) than in conventional AS, which allows much less sludge production in the MBR system and consequently, lowers the frequency of sludge disposal [13,35]. During the experimental study of MBR, sludge concentration did not exceed the withstanding limit of the membrane. The sludge generation of MBR was estimated according the increasing rate of the biomass concentration and the concentration limit for the membrane.

The detailed OPEX calculation of each treatment plant is demonstrated in the following tables. (Table 4 AS, Table 5 MBR, Table 6 MBBR).

Table 4. CAS operational cost for treating 1 m^3 wastewater.

Concept						Total Price €/m^3	Reference
(a) Consumption	**Unit**	**Amount**	**Unit**	**Unit price**	**Convert to €/m^3**	**0.55**	
Electricity	kW/m^3	0.96	€/kw	0.187	0.17952		[36]
Decolorizing agent	kg/m^3	0.2	€/kg	1.85	0.37		[37]
(b) Environmental tax	**Unit**	**Amount**	**Unit**	**Unit price**		**0.86**	
Sludge generation	kg/m^3	0.83	€/kg	0.158	0.013114		[38]
Wastewater discharge							[39]
OM [1]	kg/m^3	0.23	€/kg	1.0023	0.230529		
TSS	kg/m^3	0.32	€/kg	0.5011	0.160352		
N	kg/m^3	0.008	€/kg	0.761	0.006088		
P	kg/m^3	0.003	€/kg	1.5222	0.0045666		
Conductivity	S/cm	0.00598	€/Sm^3/cm	8.0198	0.0479584		
summation					0.449494		
ST [2] = 1.5 × SUM					0.67424101		
GT [3]					0.163		
Total price						**1.41**	

[1] OM: organic material; [2] ST: specific tax; [3] GT: general tax.

Table 5. MBR operational cost for treating 1 m^3 wastewater.

Concept						Total Price €/m^3	Reference
(a) Consumption	**Unit**	**Amount**	**Unit**	**Unit price**	**Convert to €/m^3**	**0.51**	
Electricity	kW/m^3	2.72	€/kw	0.187	0.50864		[36]
Decolorizing agent	kg/m^3	0	€/kg	1.85	0		[37]
(b) Environmental tax	**Unit**	**Amount**	**Unit**	**Unit price**		**0.43**	
Sludge generation	kg/m^3	0.023	€/kg	0.0158	0.0003634		[38]
Wastewater discharge							[39]
OM	kg/m^3	0.11	€/kg	1.0023	0.110253		
TSS	kg/m^3	0.04	€/kg	0.5011	0.020044		
N	kg/m^3	0.004	€/kg	0.761	0.003044		
P	kg/m^3	0.002	€/kg	1.5222	0.0030444		
Conductivity	S/cm	0.00533	€/Sm^3/cm	8.0198	0.04274553		
summation					0.17913093		
ST = 1.5 × SUM					0.2686964		
GT					0.163		
(c) Membrane replacement						**0.01**	[34]
(d) Maintenance and repair						**0.10**	[34]
Total price						**1.05**	

Table 6. MBBR operational cost for treating 1 m^3 wastewater.

Concept						Total Price €/m^3	Reference
(a) Consumption	**Unit**	**Amount**	**Unit**	**Unit price**	**Convert to€/m^3**	**0.27**	
Electricity	kW/m^3	0.48	€/kw	0.187	0.08976		[36]
Decolorizing agent	kg/m^3	0.1	€/kg	1.85	0.185		[37]
(b) Environmental tax	**Unit**	**Amount**	**Unit**	**Unit price**		**0.78**	
Sludge generation	kg/m^3	0.29	€/kg	0.158	0.004582		[38]
Wastewater discharge							[39]
OM	kg/m^3	0.23	€/kg	1.0023	0.230529		
TSS	kg/m^3	0.24	€/kg	0.5011	0.120264		
N	kg/m^3	0.009	€/kg	0.761	0.006849		
P	kg/m^3	0.002	€/kg	1.5222	0.0030444		
Conductivity	S/cm	0.00595	€/Sm^3/cm	8.0198	0.04771781		
summation					0.40840421		
ST = 1.5 × SUM					0.61260632		
GT					0.163		
Total price						**1.05**	

In terms of the consumption part, MBR had the highest cost (0.51 €/m^3) of electricity consumption because it required more electricity to operate and to maintain the membrane filtration. However, AS had the highest cost in the total consumption, with a value of 0.55 €/m^3, among the three treatments due to the larger amount of decolorizing agent used. This was not necessary for MBR because MBR achieved the color removal requirement and was used less in MBBR since MBBR had a better color removal performance. The reason that MBBR consumed half the electricity of the CAS system is that the HRT of MBBR was 1 day while in CAS it was 2 days, which means that MBBR with doubled treating capacity could save 50% of the electricity expense.

In regard to environmental tax, it can be observed that MBR had the lowest expense (0.43 €/m^3) since it had a better performance with organic compounds and TSS. MBBR, with half the HRT and more efficient treatment behavior, would pay a lower environmental tax (0.78 €/m^3) than the CAS system (0.85 €/m^3).

As mentioned in Section 3.3.1, the CAPEX for MBR was 366,153 €, and for MBBR it was 115,500 €, in order to improve the existing AS treatment of the studied textile industry. The only investment of MBBR in CAPEX is the carriers, and the maintenance of carriers is more convenient and economical than maintaining the membrane. Even though the OPEX of MBR and MBBR are at the same value, MBBR had the advantage of low energy consumption and competitive treatment performance. Taken together, the results of CAPEX and OPEX show that MBBR is a more attractive option for the textile industry economically.

3.3. LCA Study Results

3.3.1. Inventory Results

The inventory results of each treating process are shown in Table 7. All data are related to the functional unit (1 m^3 treated water). The impact of sludge generation was not taken into account in Simapro software; therefore, the impact of sludge generation could not be quantified in the LCA study. Nevertheless, sludge generated in the three treatments was quantified and is presented in Table 7.

Table 7. Inventory analysis of three processes.

Processes Included in LCA	Amount						Unit/FU	Ecoinvent Unit Process
	AS		MBR		MBBR			
	Input	Output	Input	Output	Input	Output		
COD	2	0.35	2	0.17	2	0.34	Kg	
TSS	0.94	0.32	0.94	0.04	0.94	0.24	Kg	
N	0.055	0.008	0.055	0.004	0.055	0.009	Kg	
P	0.008	0.003	0.008	0.002	0.008	0.002	Kg	
Color	700	315	700	140	700	267	g Pt-co	
Conductivity	6.46	5.98	6.46	5.33	6.46	5.95	mS/cm	
Wastewater	1	0.959	1	1	1	0.959	m^3	
Sludge		0.83		0.023		0.29	Kg	
decolorizing agent	0.2		0		0.1		Kg	DTPA, diethylenetriaminepentaacetic acid, at plant/RER U
Electricity	0.96		2.72		0.48		Kwh	Electricity, medium voltage, production ES, at grid/ES U

3.3.2. Environmental Impact Assessment

The environmental impact of each treatment process according to the LCA results using endpoint approach is discussed, and then the three studied treatments are compared with respect to their total environmental impact.

CAS System

The results of the environmental impact assessment are presented in points (mPt) so that different categories could be compared. Firstly, the impact of the CAS treatment process was evaluated. As shown in Table 8, the CAS process had the lowest impact on Ecosystems, while it had a major impact on Resources, followed by Human health.

Table 8. Environmental impact of CAS.

	Human Health (mPt)	Ecosystems (mPt)	Resources (mPt)
Electricity (kWh/m^3)	22.8	1.9	31.8
Decolorizing agent (kg/m^3)	34.4	3.4	81.2
TOTAL	57.2	5.3	113.0

The decolorizing agent represents 60%–70% of the environmental impact of the CAS system, having the most significant impact for all the categories.

The impact of the decolorizing agent on the detailed categories with relation to Human health, Ecosystem, and Resources is shown in Figure 4. The decolorizing agent had an impact on Human health mainly because of the effect on Climate change human health as well as Particulate matter formation categories, while Terrestrial ecotoxicity and Climate change ecosystems categories had major impacts on Ecosystems. Apart from that, the Fossil depletion category had the major responsibility for impacting Resources, while the Metal depletion category had almost no impact.

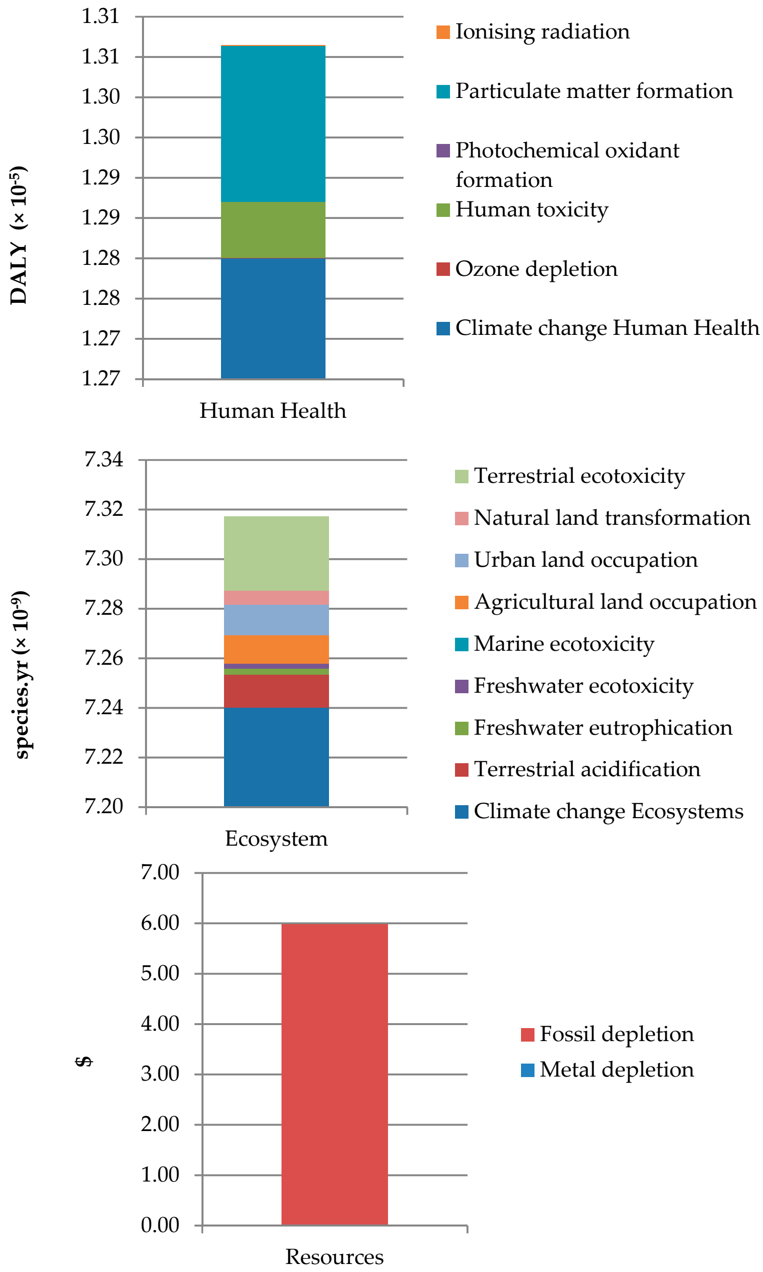


Figure 4. Analysis of the effect of the decolorizing agent on the impacted CAS categories.

MBR Treatment

In the MBR treatment, as can be seen in Table 9, there was no consumption of decolorizing agent since the system removed most of the color in the effluents. The consumption of electricity during treatment represents the total environmental impact. The results show that the impact on Ecosystem was much lower, while the major impacts were on Resources and Human Health.

Figure 5 shows the impact of electricity consumption for MBR treatment on the detailed categories related to Human Health, Ecosystem, and Resources. Climate change human health and Particulate matter formation categories were the main factors that had an impact on Human health of electricity consumption. In the meantime, the impact on Ecosystems mainly was due to Agricultural land occupation and Climate change ecosystem, while Terrestrial ecotoxicity, Natural land transformation, Urban land occupation, and Terrestrial acidification had minor impacts on the Ecosystem category. Furthermore, the major impact on Resources came from Fossil depletion category, while the Metal depletion category had almost no impact.

Table 9. Environmental impact of MBR.

	Human Health (mPt)	Ecosystems (mPt)	Resources (mPt)
Electricity (kWh/m^3)	64.6	5.4	90.1
Decolorizing agent(kg/m^3)	0	0	0
TOTAL	64.6	5.4	90.1

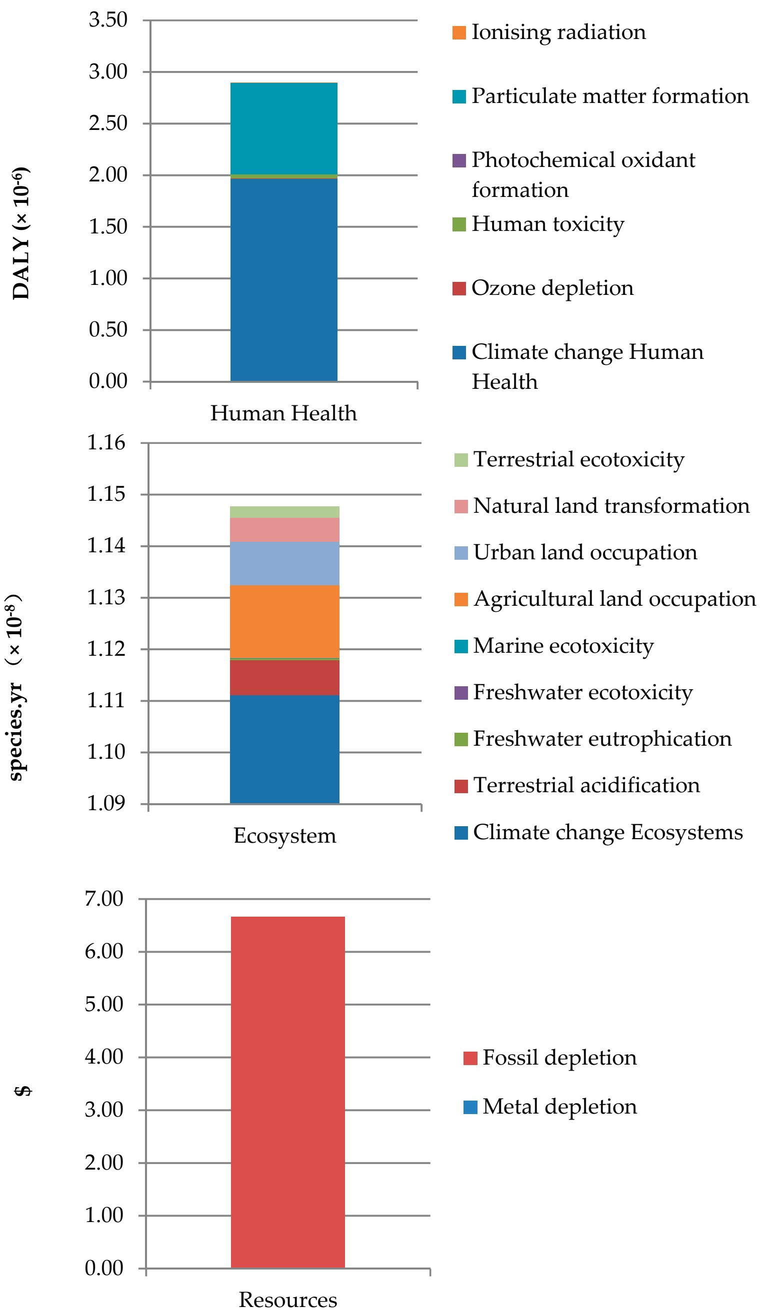


Figure 5. Analysis of the effect of electricity consumption on the impacted MBR categories.

MBBR Treatment

As shown in Table 10, MBBR treatment, like AS and MBR treatments, also had a major impact on Resources, while the impact on Ecosystem was the lowest. The environmental impact of the consumption of decolorizing agent was mainly presented in Resources.

Table 10. Environmental impact of MBBR.

	Human Health (mPt)	Ecosystems (mPt)	Resources (mPt)
Electricity (kWh/m^3)	11.4	0.9	15.9
Decolorizing agent(kg/m^3)	17.2	1.7	40.6
TOTAL	28.6	2.6	56.5

Comparison of the Three Treatments

The environmental impacts of three treatments are compared in Table 11 to evaluate which treatment had lower environmental impacts.

Table 11. Environmental impacts of the three processes.

	Human Health (mPt)	Ecosystems (mPt)	Resources (mPt)
AS	57.2	5.3	113.0
MBR	64.6	5.4	90.1
MBBR	28.6	2.6	56.5

As shown, the MBBR system had the lowest impact on all three categories. Although decolorizing agent was used in the final step of AS and MBBR to obtain a well-clarified effluent and due to the filtration, decolorizing agent was not needed for MBR, the consumption of electricity had more significant environmental impacts on Human Health and Ecosystems.

In addition to the endpoint methods, which are helpful for decision-making because results can be compared in points, midpoint analysis was also performed to help identify issues of specific environmental concerns [40]. The results of midpoint assessment are shown in Table 12. It can be observed clearly that MBBR was environmentally advantageous since most of its impacts were the lowest in most of the categories, except in Climate change Human Health, Marine eutrophication, and Freshwater ecotoxicity, which were the three impact categories associated with the use of decolorizing agent. In MBBR operation, impacts on several categories could be reduced more than 70% more than those generated in MBR, and these categories were Particulate matter formation, Terrestrial acidification, Agricultural land occupation, Urban land occupation, Natural land transformation, and Urban land occupation. The CAS system had high environmental impacts, especially on Climate change Human Health, Marine eutrophication, and Freshwater ecotoxicity, due to the amount of decolorizing agent used in the treatment.

Table 12. Comparison of three processes: midpoint analysis.

Impact Category	Unit	AS	MBR	MBBR
Climate change Human Health	kg CO_2-eq	1.29	0.19	0.65
Ozone depletion	kg CFC-11 eq	1.39×10^{-7}	7.03×10^{-8}	6.94×10^{-8}
Human toxicity	kg 1.4-DB eq	0.12	6.10×10^{-2}	6.06×10^{-2}
Photochemical oxidant formation	kg NMVOC	3.89×10^{-3}	5.58×10^{-3}	1.95×10^{-3}
Particulate matter formation	kg PM10 eq	1.95×10^{-3}	3.41×10^{-3}	9.73×10^{-4}
Ionising radiation	kg U235 eq	0.16	0.26	0.08
Terrestrial acidification	kg SO_2-eq	6.46×10^{-3}	1.17×10^{-2}	3.23×10^{-3}
Freshwater eutrophication	kg P-eq	7.84×10^{-5}	6.77×10^{-5}	3.92×10^{-5}
Marine eutrophication	kg N-eq	2.24×10^{-3}	4.27×10^{-4}	1.12×10^{-3}
Terrestrial ecotoxicity	kg 1.4-DB eq	2.96×10^{-4}	1.69×10^{-4}	1.48×10^{-4}
Freshwater ecotoxicity	kg 1.4-DB eq	7.40×10^{-3}	2.48×10^{-4}	3.70×10^{-3}
Marine ecotoxicity	kg 1.4-DB eq	1.04×10^{-3}	5.19×10^{-4}	5.18×10^{-4}
Agricultural land occupation	m^2 year	5.51×10^{-3}	1.27×10^{-2}	2.75×10^{-3}
Urban land occupation	m^2 year	2.16×10^{-3}	4.34×10^{-3}	1.08×10^{-3}
Natural land transformation	m^2 year	1.25×10^{-5}	2.67×10^{-5}	6.27×10^{-6}
Water depletion	m^3	1.12×10^{-2}	8.10×10^{-3}	5.60×10^{-3}
Metal depletion	kg 1 Fe eq	2.02×10^{-3}	2.08×10^{-3}	1.01×10^{-3}
Fossil depletion	kg oil eq	5.17×10^{-7}	4.14×10^{-7}	2.59×10^{-7}

3.4. Reuse of the Treated Effluent

Taking into account the previous results of economic and LCA analyses, MBBR treatment was selected as the most feasible method to be applied at industrial scale. At this point, the possibility of reusing the treated wastewater in a new dyeing processes was determined. MBBR was selected to check if the removal results of COD, SST, and color were sufficient to make new dyes without their quality being affected by the presence of organic matter residues, suspended solids, and residual dyes.

One hundred percent of the treated water from the MBBR process was reused for a new dyeing process. Three reactive dyes—Yellow Procion HEXL, Crimson Procion HEXL, and Navy Procion HEXL—were used in the water reuse study. The color differences with respect to a reference dyeing are shown in Table 13. $DE_{CMC(2:1)}$ values of all three dyes were lower than 1, which is the acceptable limit for the textile industry. The results imply the feasibility of MBBR treatment to obtain a water reuse proportion up to 100% in the new dye baths. It should be considered that in practical textile production, there is 30% water loss due to evaporation or water fixed into the textile products. Therefore, the wastewater generated accounts for 70% of freshwater consumed by the industry. Although all the treated water was reused, it is not equal to 100% of the total water consumed by the industry. If we wanted to reuse all treated water, this would be 70% of the water consumed.

Table 13. Color differences between fabrics dyed with the treated effluent and a reference dyeing.

Reactive Dyes	100% Effluent Reused $DE_{CMC(2:1)}$
Yellow Procion HEXL	0.55 ± 0.08
Crimson Procion HEXL	0.76 ± 0.07
Navy Procion HEXL	0.42 ± 0.01

A comparison of the cotton fabrics dyed with the three dyes studied is shown in Figure 6.

Figure 6. Comparison of cotton dyeings made with the three dyes studied.

4. Conclusions

After carrying out the comparative study in three pilot plants with CAS, MBR, and MBBR technologies, MBBR showed that it was a better alternative than CAS, with a comparable COD removal rate to CAS and a more efficient color reduction, while the treating capacity was doubled. Although the MBR was the most efficient technology for organic compounds and color removal, the economic and LCA study suggested that MBBR is a more attractive option for textile wastewater treatment at an industrial-scale plant. MBBR had the same OPEX as MBR, both lower than that of the CAS system, but MBBR had lower investment costs and lower CAPEX, which was 68% less than the CAPEX of MBR. MBBR also largely reduced the environmental impacts on different categories with respect to CAS and MBR processes in general. MBBR reduces the environmental impact as compared with the AS, since it reduced the consumption of electricity and decolorizing agent with respect to AS. MBR had a higher electrical consumption but avoided the consumption of decolorizing agent.

Finally, new dyes made with treated water from MBBR met the quality standard for the textile industry ($DE_{CMC(2:1)} \leq 1$). The presence of organic matter residues, suspended solids, and residual dyes in the effluent of MBBR did not affect the dyeing quality. Reuse of wastewater up to 100% is very promising in the textile industry as it is a considerable water-consuming industry worldwide.

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