



SUSTAINABLE MANAGEMENT OF INDUSTRIAL WASTEWATER IN TÜRKİYE: PILOT-SCALE GRAVITY-DRIVEN DYNAMIC MEMBRANES FOR WATER REUSE

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Abstract: There is an urgent need to transition toward a circular economy in Türkiye by improving effluent quality for industrial water reuse. This study evaluates the management and performance of a sustainable, pilot-scale (170 L) gravity-driven dynamic membrane (GD-DM) system designed for low-energy wastewater reclamation. Unlike conventional high-pressure membrane systems that suffer from high energy demands and chemical cleaning requirements, this GD-DM system integrate a 150 µm stainless steel support material to obtain a very low turbidity water. To align with waste-to-resource principles, the dynamic membrane layer was formed using waste activated sludge from the return line of an organized industrial wastewater treatment plant, eliminating the need for synthetic filtration media. Operating with automated sensors for real-time turbidity and flow monitoring, the system achieved an average flux of 353 L/m².h. High-quality reclaimed water (turbidity < 5 NTU) was consistently produced within 3 minutes, with levels dropping below 1 NTU for over 84% of the operational cycle. Because the conductivity of the permeate is very high (above 4,301 µS/cm), it cannot be reused for agricultural purposes. This approach provides a microfiltration-level effluent quality while maintaining a flux 20–30 times higher than traditional polymeric membranes. The treated water is virtually suspended-solids-free, making it suitable for industrial reuse. By drastically reducing energy consumption and operational complexity, the GD-DM system offers a scalable and environmentally sustainable solution for managing industrial wastewater and protecting receiving environments from pollutants like microplastics.

Keywords: Industrial wastewater, Gravity-driven, Activated sludge, Turbidity, Dynamic membrane, Reuse

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Received: January 29, 2026

Accepted: March 01, 2026

Published: March 15, 2026

Cite as: Uyanik, İ. (2026). Sustainable management of industrial wastewater in Türkiye: Pilot-Scale gravity-driven dynamic membranes for water reuse. *Black Sea Journal of Engineering and Science*, 9(2), 928-933.

1. Introduction

Water crises are being experienced in all over the world, which is triggered by global climate change, along with population growth and industrialization (Islam, 2022; Turna & Solmaz, 2022). Water resources are threatening by these phenomena. Domestic and industrial wastewaters resulting from the overuse of water resources are treated in treatment plants and generally discharged into a receiving water body (Bayram, 2025). There is a need for water reuse and conservation to protect these water resources (Islam, 2022).

One of the best existing techniques developed for water reuse is membrane technology (Foorginezhad et al., 2025). Although membrane systems have advantages such as obtaining very high quality water and long (5-10 years) operating periods, they have many disadvantages (Das et al., 2022). These include high initial investment and operating costs, the need for qualified technical personnel, management problems of the resulting concentrate, chemical consumption due to clogging problems and consequently wastewater generation

(Stoffel et al., 2023), these problems are leading our country to turn to alternative systems instead of membrane systems (Hiz & Arslan, 2025).

Dynamic membrane (DM) technology aims to create a layer using a support layer as an alternative to membrane systems, thus mimicking the work of membranes with the help of a layer that acts like a membrane (Liu et al., 2009). The created layer is generally called a cake layer, but in the literature, filtration can be performed on the support layer with different accumulation materials (Kizilet et al., 2022). This layer can be achieved by pre-accumulation (Anantharaman et al., 2020), or it can be self-formed directly in the reactor (Millanar-Marfa et al., 2022). In the literature, it is mostly preferred in anaerobic and aerobic membrane bioreactors (MBRs) (Yurtsever et al., 2017). DM technology also has some drawbacks, one of which is the fluctuations in effluent water quality and the need to recreate the layer in each filtration cycle. This necessitates a more careful operating process (Saleem et al., 2017).

Another innovative system in membrane technology is



gravity driven (GD) membrane systems (Pronk et al., 2019). Polymeric membranes are used in GD systems, which are mostly preferred in rural areas for river water and drinking water treatment (Pronk et al., 2019). Studies combining DM technology with GD-operated filtration systems have been increasing in recent years (Chen et al., 2024). In GD membrane systems, instead of obtaining water at a constant flow with vacuum (pump), which is the driving force in MBRs, variable flows of effluent water can be obtained with the effect of a constant pressure driving force provided by a constant water head (Song et al., 2024). This promises a tighter and more stable cake layer (Elbir et al., 2024). Therefore, the quality fluctuations and cake layer deterioration in the effluent water mentioned above can be prevented. In a study using GD-DMBR in the treatment of domestic wastewater, it was observed in pilot-scale studies that inorganic clogging was prevented with a support layer with a diameter of 25 μm and the resistance in the cake layer decreased at low pressure (Liu et al., 2025). Similarly, in a laboratory-scale study where plastic recycling plant wastewater was treated using a GD-DM filtration tank, both high flux and high water quality were achieved (Colakoglu et al., 2025). In GD-DM systems, operating at constant pressure and variable flux necessitates a compromise in effluent water quality due to the high pore size. Although pore sizes up to 500 μm have been reported in the literature (Kiso et al., 2005), it has been determined that a maximum pore size of 300 μm is required to ensure the production of high-quality wastewater (<5 NTU); beyond this threshold, the desired water quality cannot be achieved (Colakoglu et al., 2025; Elbir et al., 2024; Saleem et al., 2017). Therefore, new GD-DM studies with high pore sizes are needed.

In Türkiye, there are studies on the use of domestic wastewater for agricultural purposes or as a new water source (Nas & Yılmaz, 2019). However, it has been noted that irrigation water standards cannot be met, especially in terms of turbidity, electrical conductivity, and sodium parameters (Bingül & Altıkat, 2017). Other studies have also indicated that treated water can be treated using membrane technology (Coskun et al., 2016; Komesli et al., 2015). Therefore, new studies on the reuse of water are needed. This study investigated the efficacy of a Gravity-Driven Dynamic Membrane (GD-DM) system for the tertiary treatment of municipal wastewater treatment plant (WWTP) effluent, aiming to achieve permeate quality comparable to conventional membrane filtration. To this end, flat-plate DM modules were configured using stainless steel mesh support, and the development of the dynamic layer—formed through the interaction of WWTP effluent and activated sludge—was systematically monitored in a pilot-scale plant. The findings are expected to establish GD-DM technology as a cost-effective and sustainable alternative to traditional membrane systems for water reclamation and reuse applications.

2. Materials and Methods

2.1. Materials

The pilot-scale GD-DM filtration tank was constructed from polyethylene (PE) in a cylindrical geometry, featuring a total volume of 200 L and an operational volume of 170 L. Process monitoring was facilitated by two online turbidimeters (Solitax t-line, Hach, Germany), positioned within the tank and on the effluent line. Three level sensors (ASP 12U, China) were installed to monitor tank levels. The filtration unit consisted of eight custom-fabricated modules, each measuring approximately 17.5 x 21.5 cm. These modules utilized an SS304 stainless steel mesh with a 150 μm pore size mounted on both sides of a PVC frame, providing a total surface area of roughly 0.6 m^2 .

A 300 L PE tank was utilized for treated water storage, while a 35 L PE tank was used to sludge feeding. Fluid circulation and sludge delivery were managed by a 0.750 kW centrifugal pump (Duffmart QB80, China) with a rated capacity of 2500 L/h. The modules were manifolded into a single line using DN20 PE pipes, integrated with an inline flowmeter (0.5–25 L/min, Serrata, China) and a turbidimeter. Liquid flow control across the system was maintained through a combination of manual and motorized valves (Convolve CSBVM220, China).

2.2. Operational Procedure of Pilot Scale GD-DM Filtration Tank

In this study, the treated wastewater from the Kayseri Organized Industrial Zone (OIZ) WWTP is continuously fed into the filtration tank as raw water by a pump using level sensor (LS1 and LS2, Figure 1) and automation system. The activated sludge is also fed from WWTP recirculation unit at a concentration of approximately 600 mg/L in filtration tank. The effluent turbidity is continuously monitored, and treated water is converted to the clean water tank when the turbidity is below 5 NTU. The schematic diagram of the pilot-scale system is presented in Figure 1.

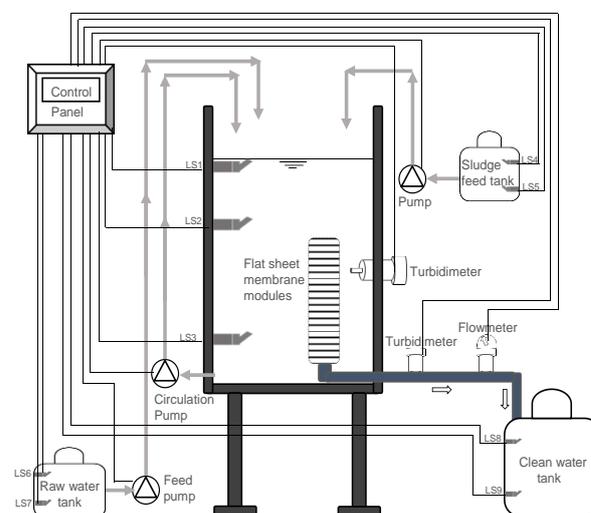


Figure 1. A schematic diagram of pilot-scale dynamic membrane filtration system.

2.3. Analysis

The SS analysis was performed according to SM 2540D. Turbidity measurements in the filtration tank and in the permeate were monitored online using a turbidimeter (Solitax t-line, Hach, Germany) operating according to DIN EN ISO 7027 principles and employing dual infrared scattered light technology. Conductivity is measure as $\mu\text{s}/\text{cm}$ with Hach HQ40D (Germany). Flux was also calculated according to the flow rate and using the equation 1.

$$\text{Flux (L/m}^2\cdot\text{h)} = \frac{\text{Flow (L/min)} \cdot 60 \text{min/h}}{\text{membrane area (m}^2\text{)}} \quad (1)$$

3. Results

The results obtained during 213 minutes of operation of the pilot-scale GD-DM system was presented in Figures 2 and 3. The change in flow rate and effluent turbidity parameters over time were shown in Figure 2. Before operation began, 15 L of activated sludge with a concentration of 6500 mg/L was fed into the tank, and approximately 580 mg/L of suspended solids (SS) was measured in the tank. A turbidity of 220 NTU was measured by the submersible turbidity sensor in the tank. While the turbidity of the effluent was measured as 56 NTU at the beginning, it decreased to 3.2 NTU by third minute and fell below 2 NTU at the 6th minute. As a result of the gradual thickening of the cake layer accumulating on the surface of the filtration modules, the turbidity fell below 1 NTU at minute 33. Small decreases in turbidity levels were recorded over the following 180 minutes, with an average of 0.49 NTU and 0.28 NTU at the end of the 180th minute. The turbidity of the effluent water was reduced to below 5 NTU in approximately 3 minutes and did not rise above 5 NTU for the remaining 210 minutes. In the following minutes, a tendency to decrease in flow rate was observed following the condensation of the cake layer on the modules. While the flow rate showed a faster decrease in the first hour of the operation, it showed a slower decrease in the following two hours, gradually falling from 3.21 to 1.83 L/min.

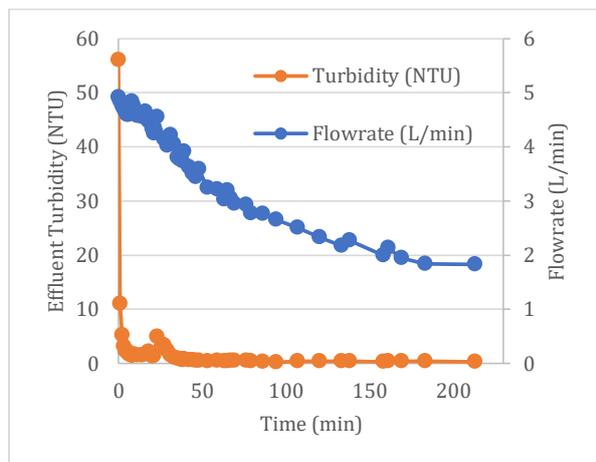


Figure 2. Changes in flow rate and permeate turbidity parameters.

The graph showing the change in flow rate per unit membrane area per unit time (flux) is presented in Figure 3. The change in flux, while the initial flux was 491 LMH during the initial operation of the tank, it decreased over time following the formation of a cake layer on the filter modules. The flux value measured at the point where the 5 NTU drinking water standard was met according to WHO standards was 470 LMH (Rahmanian et al., 2015). Accordingly, while the flux was measured as 491 L/m²-hr (LMH) when the tank was began to operate, it decreased to 459 LMH at 5 minutes and 433 LMH at 20 minutes as the thickness of the cake layer increased. At 33 minutes, when the effluent turbidity value dropped to 1 NTU, it was measured as 405 LMH. Finally, at 125 and 180 minutes, values of 233 LMH and 184 LMH were calculated, respectively.

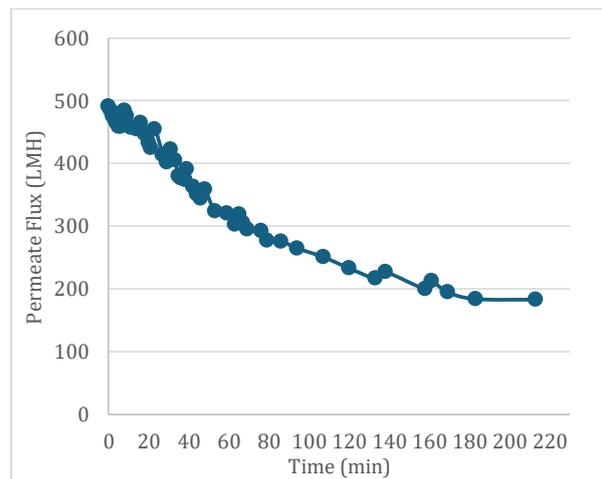


Figure 3. Permeate flux profile over time.

To clean the cake layer formed after filtration, the concentrate in the tank was recirculated back into the reactor for 3 minutes using a pump to create turbulence. This procedure, which was expected to remove the cake layer from the surface, was partially successful. However, more successful results could be obtained with longer recirculation or by changing the tank geometry. Images of the modules after recirculation are given in Figure 4.



Figure 4. Photographs of both surfaces of the modules after the cleaning procedure.

4. Discussion

When DM studies in the literature are investigated, it is seen that treatment is achieved in biological reactors with the help of a self-forming cake layer and the effluent quality is monitored (Lv et al., 2022). During this process, the wastewater containing biological sludge in the effluent at the beginning of operation is recirculated back into the system (Sanchis-Perucho et al., 2022). Because in a system where biological treatment is performed, the presence of sludge (bacteria) in the system is important for biological activity such as sludge age (Chen et al., 2025). However, in the present study, biological activity is neglected for the sludge fed into the system. Therefore, there is no need to recirculate the sludge back into the system. For this reason, this membrane system is named as a filtration tank rather than a reactor.

According to the Water Pollution Control Regulation in Türkiye, the SS concentration in the effluent of existing WWTPs in Türkiye has a limit of 200 mg/L for 2-hour samples in OIZs (Burak et al., 2022). Therefore, the activated sludge formed after biological treatment may be discharged without being settled sedimentation tanks. Also, it is reported that WWTPs are point sources for MPs, especially due to increasing microplastic pollution (Baycan et al., 2025; Çolakoğlu et al., 2026). Therefore, cost-effective membrane systems for WWTP effluents can be an effective solution for the protection of receiving environments. Although existing conventional membrane systems, MF and ultrafiltration, provide good quality effluent, their initial investment and operating costs are higher compared to DMs. According to the results obtained in this study, the effluent quality has a turbidity value below 1 NTU for more than 84% of the operating period. In a study monitoring the turbidity of the effluent water with an MF membrane for drinking water treatment, the lowest, average, and highest turbidity values were measured as 0.6, 2.8, and 6.2 NTU, respectively (Safaei et al., 2022). In another study where river water was treated, effluent turbidity values of 2.7 and 0.86 NTU were observed in polypropylene and ceramic membranes with pore sizes of 1 µm and 0.5 µm, respectively (Al-Tamimi et al., 2024). Therefore, the turbidity values below 1 NTU obtained in the present study were found to be more effective compared to alternative filtration and membrane systems.

Similarly, in polymeric membrane systems, flux values of 10 LMH (subcritical flux), 15, and 18 LMH were studied, and a flux value of 35 LMH was determined as the supercritical flux (Xu et al., 2023). In another study, modified membranes were used, and even the highest fluxes during reactive dye removal remained below 100 LMH (Vatanpour et al., 2025). In the current study, the highest flux was 470 LMH below 5 NTU, while the average flux was 353 LMH. Therefore, this study has shown that similar quality water can be obtained with less membrane area and space requirement compared to polymeric membranes.

Reuse of treated wastewater is a key component of future

water strategies of Türkiye. A study conducted across 618 WWTPs in various regions identified 6.2 billion m³ of water as being suitable for reuse. In this study, despite the effective removal of SS and turbidity, the electrical conductivity (EC) of the treated effluent (4.3±0.6 ms/cm) remains a critical limiting factor for its direct reclamation in agricultural irrigation. Within the regulatory framework for water reuse in Türkiye, high salinity levels pose significant risks to soil structure and crop productivity (Karahan et al., 2025). The elevated conductivity observed in this study suggests that the water cannot be classified as immediately reusable for salt-sensitive agriculture. This indicates that while the GD-DM system is highly effective for particle separation, a secondary desalination step—such as reverse osmosis (RO) or ion exchange—would be required to mitigate the salinity hazard and meet irrigation water criteria for sustainable irrigation.

Conversely, the physical quality of the permeate provides a distinct advantage. The low turbidity and near-complete absence of SS in the effluent make it an excellent candidate for internal process reuse within the treatment plant. Specifically, the high clarity of the water ensures that it can be utilized in belt press units for polymer preparation and belt washing without the risk of nozzle clogging or equipment fouling. Reusing this low-turbidity water in other industrial activities would not only reduce the plant's freshwater footprint but also optimize the mechanical strength of existing infrastructure, presenting a viable circular economy application for the GD-DM technology.

5. Conclusion

In this study, the effluent from the KOIZ WWTP treatment plant was treated with a GD-DM system, and the water quality was monitored. Eight filtration modules, manufactured as flat sheet with a pore size of 150 microns, were mounted in a 170 L tank, and instantaneous turbidity and flow rate measurements were performed. In this system, where the effluent of the KOIZ WWTP is filtered, the dynamic layer was created by feeding activated sludge from the recirculation unit of the same facility. In the system, which was operated for a total of 213 minutes, the effluent turbidity value dropped below 1 NTU after 33 minutes and operated stably for 180 minutes. This pilot study showed that the GD-DM system is highly effective in filtering the effluent of the KOIZ-WWTP. The GD-DM technology proves to be a robust solution for particle separation in municipal wastewater treatment. While chemical parameters like conductivity necessitate further treatment for agricultural applications, the system provides a viable pathway for industrial-grade water reuse, contributing significantly to sustainable water management and the reduction of industrial freshwater demand.

Author Contributions

The percentages of the author' contributions are presented below. The author reviewed and approved the final version of the manuscript.

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C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

Acknowledgements

This study was supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under Grant no. 2240584 (1812). The author thanks TUBITAK TEYDEB for their support. The author would also like to express sincere gratitude to Kayseri Organized Industrial Zone Wastewater Treatment Plant workers, and Mizan Arıtma Teknolojileri A.Ş., a company operating within Erciyes Technopark for their valuable support.

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