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Evaluation of Treatment and Reuse Potential of Textile Wastewaters: A Case Study from Denim Production

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ABSTRACT

The textile sector is highly water-intensive and generates wastewater with complex and variable chemical characteristics. In denim production, dyeing and stone-washing processes contribute to elevated organic load, suspended solids, color, and salinity. This study evaluates the performance of conventional and advanced treatment technologies using field data from a denim facility located in the water-stressed Meriç–Ergene Basin. The treatment system consists of primary treatment, extended aeration activated sludge, ultrafiltration (UF), and reverse osmosis (RO). Influent concentrations were 336 mg/L COD, 368 mg/L total suspended solids, and 262 Pt-Co color. Biological treatment achieved approximately 87% COD removal but showed negligible conductivity reduction, indicating limited salt removal. UF effectively removed suspended solids yet provided only partial reduction of dissolved constituents. After RO treatment, COD decreased to 4 mg/L, conductivity to 10 µS/cm, and color to 4 Pt-Co, satisfying international reuse criteria. The findings indicate that compliance with discharge standards does not guarantee suitability for process water reuse and emphasize the necessity of membrane-based advanced treatment to support water circularity in textile production, particularly in water-scarce regions.

Keywords: Textile wastewater; Membrane treatment; Conductivity; Water reuse

1. INTRODUCTION

Global water stress has become a fundamental sustainability challenge for all industrial sectors due to population growth, climate change, and intensive water use. Freshwater consumption in industrial processes and the associated generation of wastewater increase pressure on water resources and contribute to the deterioration of receiving water bodies (Sayam et. al. 2025; Arastou et. al. 2025). In this context, the textile industry, characterized by high water consumption and significant wastewater production, is considered one of the leading sectors in global water management discussions.

The demand for textile products continues to increase in parallel with population growth and economic development, and this trend is expected to persist in the coming years (Sandin and Peters, 2018). In particular, the fast fashion production model further intensifies water consumption and wastewater generation due to short product life cycles and high production volumes. The textile and fashion industry is reported to use approximately 93 billion m³ of water annually, accounting for a significant share of global freshwater withdrawals and contributing nearly 20% of total global industrial wastewater generation (Jegatheesan et. al., 2016; World Bank, 2019).

According to data from the European Environment Agency, the production chain of textile products purchased by European Union households in 2022 required approximately 6 billion m³ of freshwater, with about 85% of this water footprint occurring outside Europe, particularly in Asian regions where production is concentrated (EEA, 2025). Türkiye is one of these regions and ranks 7th globally among the top 10 textile-exporting countries, with an export value of approximately 35-40 billion USD (World Population Review, 2026).

1.1. Water Use in the Textile Sector

Textile production is widely recognized as one of the most water-intensive industrial activities, as water functions not only as a cleaning medium but also as a carrier for dyes and finishing chemicals (Samsami et al., 2020). Depending on fiber type, product specifications, and process configuration, water consumption typically ranges between 30 and 400 L per kilogram of processed fabric (Ozturk et al., 2016; Yukseler et al., 2017). Wet processes such as dyeing and finishing account for more than 80% of total sectoral water use and are characterized by intensive chemical inputs (Ergül, 2014). On a process basis, water demand varies from 2.5-25 L/kg in desizing and bleaching, 20-45 L/kg in scouring, and 17–32 L/kg in mercerization, while cotton dyeing may require 70-150 L/kg (Arastou et al., 2025; Kumar et al., 2021).

This extensive water use directly translates into the generation of large volumes of wastewater containing residual dyes, auxiliary chemicals, suspended solids, and dissolved salts. The variability in fiber types and applied chemicals results in wastewater with fluctuating composition and complex pollutant profiles. If inadequately treated, these effluents can cause severe impacts on receiving water bodies, including color contamination, increased salinity, and reduced dissolved oxygen levels. Projections suggest that textile-related wastewater pollution may double by 2050, emphasizing the urgency of improving water efficiency and treatment strategies (Sharma et al., 2023).

1.2. Characterization of Textile Wastewater

The composition of textile wastewater varies significantly depending on fiber type, applied dyes, auxiliary chemicals, and specific production processes (Ribeiro et al., 2017). Fluctuations in pH and temperature, together with the presence of poorly biodegradable dyes and chemical additives, complicate treatment operations and limit the effectiveness of conventional biological systems. Approximately 3,600 dye types and nearly 8,000 chemical substances are used in textile processes such as bleaching, dyeing, printing, and finishing (Atalay Eroğlu & Akbal, 2025), and the textile sector is estimated to account for a substantial proportion of global dye-containing wastewater discharges (Katheresan et al., 2018).

Textile wastewaters are typically characterized by high chemical oxygen demand (COD), intense color, elevated salinity, and significant suspended solids. Wet processes, particularly dyeing and finishing, constitute the primary sources of pollution due to intensive chemical inputs and repeated washing steps. Representative pollutant ranges reported in the literature are summarized in Table 1.

Denim production follows the general structure of textile manufacturing but introduces additional pollutant loads due to indigo dyeing and specific finishing treatments. Indigo dyeing generates intensely colored effluents with distinct organic characteristics. In particular, stone-washing processes employing pumice stones create significant mechanical abrasion, leading to the release of fragmented pumice particles, fibers, and residual dye into the wastewater stream. This results in elevated total suspended solids (TSS) concentrations and increased sludge production (Yukseler et al., 2017). Furthermore, chemical fading treatments using oxidants such as sodium hypochlorite or potassium permanganate alter the organic pollution profile and may contribute to higher salinity and residual oxidant-related by-products. Compared to conventional textile production, these combined processes increase both pollutant variability and treatment complexity in denim wastewater.

Table 1. Typical Pollution Parameters of Textile Wastewater

Parameter	Unit	Typical Range / Average	References
Chemical Oxygen Demand (COD)	mg/L	500 - 30.000	Ben Amar et. al., 2009; Ergül, 2014; Jegatheesan et. al., 2016; Yukseler vd., 2017; Zhou and Zhou, 2019
Color	Pt-Co	500 - 10.000	
pH	-	6.0 - 12	
Total Suspended Solids (TSS)	mg/L	50 - 8.500	
Electrical Conductivity	µS/cm	1.500 - 35.000	
Oil and Grease	mg/L	10 - 168	
Phenol	mg/L	1.3-155	

1.3. Treatment and Reuse of Textile Wastewater

Textile wastewater is considered one of the most complex industrial effluents due to poorly biodegradable compounds, fluctuating pH, high color intensity, and salinity. These characteristics often require multi-stage treatment systems to achieve acceptable effluent quality (Atalay Eroğlu & Akbal, 2025). Treatment approaches can broadly be classified as conventional and advanced technologies.

Conventional treatment typically includes primary processes (screening, sedimentation), neutralization, and biological treatment, often combined with coagulation–flocculation. Coagulation–flocculation is widely applied for the removal of color and colloidal pollutants through particle destabilization and sedimentation (Golob et al., 2005). Biological systems such as activated sludge effectively remove biodegradable organic matter and reduce COD; however, many dyes and auxiliary chemicals exhibit low biodegradability, limiting complete removal (Rai et al., 2005). While conventional systems are efficient in reducing suspended solids and biodegradable fractions, they are generally insufficient for eliminating residual color, dissolved salts, and refractory compounds. In particular, the limited removal of salinity significantly restricts water reuse potential (Solak & Ozturk, 2018; Yükseler et al., 2017).

To overcome these limitations, advanced treatment technologies are applied to enhance effluent quality and enable reuse. Advanced oxidation processes (AOPs) generate highly reactive radicals capable of degrading persistent organic pollutants and dye molecules (Bilinska & Gmurek, 2021; Torrades et al., 2014). Although effective for color and refractory organics removal, AOPs do not address dissolved salts. Membrane-based processes, including ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), provide physical separation of contaminants. UF primarily removes suspended solids and macromolecules, whereas NF and especially RO enable substantial removal of dissolved salts and low-molecular-weight compounds (Ranganathan et al., 2007). RO systems, in particular, can achieve high-quality permeate suitable for process water reuse, although elevated salinity increases energy demand.

Consequently, hybrid treatment configurations combining biological processes with advanced oxidation and membrane systems are increasingly recognized as essential for achieving water recovery in textile operations, particularly in water-scarce regions.

1.4. Reuse of Textile Wastewater

Due to the complex and variable composition of textile effluents, achieving water quality suitable for reuse generally requires integrated treatment configurations combining biological, physicochemical, and advanced processes. While conventional systems effectively reduce organic load and suspended solids, they are typically inadequate for meeting reuse criteria, particularly regarding residual color and salinity. AOPs contribute to the degradation of refractory organic compounds, whereas membrane technologies such as NF and RO enable substantial removal of dissolved organics and ions, producing effluents compatible with industrial reuse requirements.

Water reuse in the textile sector offers significant environmental and economic advantages by reducing freshwater abstraction and minimizing wastewater discharge, especially in water-scarce regions. The European Union BAT/BREF documents recognize treated wastewater reuse as a strategic component of sustainable textile production. Similarly, Chinese technical guidelines define quality-dependent reuse categories for process water and auxiliary applications (Zhou & Zhou, 2019). In Türkiye, however, no sector-specific regulation exclusively defines reuse criteria for textile wastewater. Consequently, reuse feasibility is commonly assessed using international reference standards and evaluated on a facility-specific basis under regulatory supervision.

Against this background, the present study provides a focused overview of textile wastewater treatment and reuse approaches and presents a field-scale assessment of a membrane-integrated wastewater treatment and recovery system implemented in a denim production facility located in the water-stressed Meriç-Ergene Basin. By comparatively evaluating discharge compliance and reuse suitability, the study aims to highlight the limitations of conventional treatment and to demonstrate the critical role of advanced membrane processes in enabling industrial-scale water reuse in textile production.

2. MATERIALS AND METHODS

2.1. General Characteristics of the Facility

Within the scope of this study, the reuse application of wastewater generated from a textile industry performing denim dyeing, bleaching, and washing processes was evaluated based on selected pollutant parameters. The facility is located in the Meriç-Ergene Basin in northwestern Türkiye, a region experiencing significant water stress. This regional condition makes water recovery and reuse practices a strategic necessity for the operation of the plant.

Pumice stones are used in the denim bleaching processes at the facility. While the mechanical abrasion provided by pumice enables the desired visual and physical characteristics of the fabric, it also significantly affects wastewater characteristics. In particular, the increase in TSS enhances the importance of primary treatment and filtration stages within the treatment system.

The wastewater treatment plant at the facility consists of primary treatment, biological treatment, and advanced treatment units. A schematic representation of the wastewater stream and treatment processes is presented in Figure 2. The primary treatment section includes primary sedimentation tanks, an equalization tank, and rotary drum screens. The biological treatment unit is based on an extended aeration activated sludge process. Following biological treatment, UF and RO are applied as advanced treatment steps, and a portion of the treated water is reused within the facility. This integrated approach contributes to both the reduction of freshwater consumption and the decrease in discharged wastewater volumes.

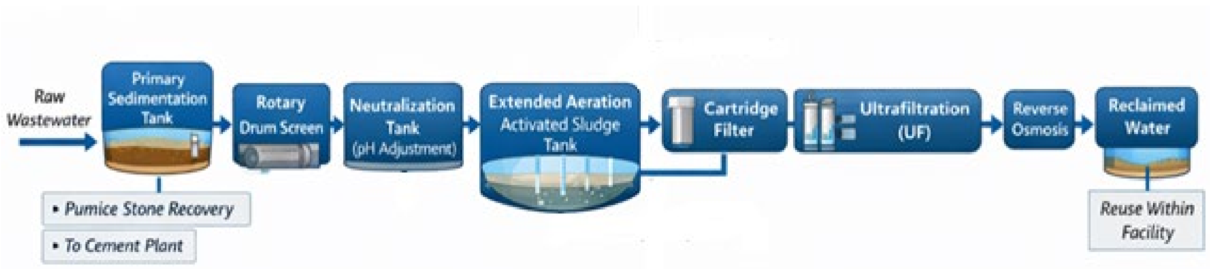

Figure 2. Wastewater Treatment Plant and Water Reuse Process Flow Scheme

2.2. Wastewater Analysis

In the investigated textile wastewater treatment plant, grab samples were collected on three different occasions from four sampling points: influent, biological treatment effluent, UF effluent, and RO effluent, in order to evaluate treatment performance. All samples were analyzed in an accredited laboratory. The analyses were conducted in accordance with the *Standard Methods for the Examination of Water and Wastewater* (APHA, 2017). The following parameters were determined: pH (SM 4500 H^+ B), electrical conductivity (SM 2510 B), chemical oxygen demand (COD) (SM 5220 B), total suspended solids (TSS) (SM 2540 D), color (SM 2120 C), and phenol (SM 5530 B, D). The obtained results were used to assess pollutant removal efficiencies and to evaluate the potential for water reuse.

3. RESULTS AND DISCUSSION

The analytical results of the samples collected from the facility are presented in Table 2. The table includes water quality parameters measured at the influent, biological treatment effluent, UF effluent, and RO effluent points, together with the overall removal efficiencies achieved across the treatment system.

In Table 3, a comparative assessment is provided for the conventional and advanced treatment stages. The conventional treatment effluent was evaluated against the discharge limits defined in the Turkish Water Pollution Control Regulation (SKKY, 2004-Textile Finishing - Table 10.2). For reuse evaluation, since there is no specific binding regulation governing wastewater reuse in Türkiye, the advanced (RO) effluent was compared with the Class II criteria of the Turkish Surface Water Quality Regulation (SWQR, 2012), as well as with the reuse benchmarks specified in the EU BREF document and the technical standards issued by the Ministry of Ecology and Environment of China (Zhou and Zhou, 2019).

Table 2. Treatment Performance and Removal Efficiencies

	Unit	Influent	Biological Treatment Effluent	Ultrafiltration Effluent	Reverse Osmosis Effluent	Total removal
pH	-	7.0	7.51	7.53	6.82	-
Conductivity	us/cm	1322	1307	1281	10	99.2%
COD	mg/L	336	45.4	40.7	4	98.8%
TSS	mg/L	368	50.6	0	0	100%
Color	Pt-Co	262	92.9	70.08	4	98.5%
Phenol	mg/L	0.32	0.09	0.09	0.09	>72.1%

Table 3. Comparison of effluent quality with discharge, surface water and reuse standards

Results and Criterias	**pH**	**Conductivity µs/cm**	**COD mg/L**	**TSS mg/L**	**Color Pt-Co**	**Phenol mg/L**
Conventional Treatment Effluent	7.51	1307	45.4	50.6	92.9	0.09
SKKY Discharge Limit (SKKY, 2004)	*6-9*	-	*400*	*140*	*280*	*1*
Advanced Treatment Effluent	6.82	10	4	0	4	0.09
Turkish Surface Water Qual. Reg.-Class II Water Quality Values (SWQR, 2012)	*6-9*	*1000*	*50*	-	-	-
EU BREF – Reuse Criteria (Yukseler et. al., 2017)	*6-8*	*1000*	*80*	*5*	*20*	-
China MEP – Reuse Criteria (Zhou and Zhou, 2019)	*6-9*	*<1500*	*<50*	*<30*	*25*	-

The raw wastewater exhibited elevated COD (336 mg/L), TSS (368 mg/L), color (262 Pt-Co), and phenol (0.32 mg/L) levels, reflecting the organic and suspended solid loads generated by dyeing, bleaching, and stone-washing operations in denim production. In particular, the use of pumice stones in stone-washing significantly contributes to high TSS concentrations. Table 3 distinguishes between compliance with national discharge standards (SKKY - Water Pollution Control Regulation, 2004) and suitability for water reuse. Although the conventional biological effluent complies with SKKY discharge limits, it fails to meet the more stringent reuse criteria, especially regarding conductivity and color.

Following biological treatment, a significant reduction in organic pollution was achieved; the COD value decreased to 45.4 mg/L, corresponding to approximately 87% removal efficiency. Similarly, substantial decreases were observed in TSS and phenol concentrations. In contrast, the conductivity value showed no meaningful change after biological treatment (from 1322 µS/cm to 1307 µS/cm), clearly indicating that dissolved salts are not removed through biological processes. This finding shows that biological treatment alone cannot control salinity; although the effluent meets national discharge standards, it remains unsuitable for process water reuse, revealing the limitations of discharge-oriented treatment design in water-scarce regions.

At the UF stage, suspended solids were completely removed, and the color value decreased to 70 Pt-Co. However, the reduction in COD remained limited (40.7 mg/L), and no significant change in conductivity was observed (1281 µS/cm). These results indicate that the UF process is effective in removing particulate and macromolecular components but is not sufficient on its own for the removal of dissolved organic and inorganic substances.

RO, a substantial improvement was observed across all quality parameters. The COD value decreased to 4 mg/L (98.8% total removal), conductivity declined to 10 µS/cm (99.2% removal), and color was measured at 4 Pt-Co. These results demonstrate the decisive role of pressure-driven membrane processes in removing dissolved salts and low-molecular-weight organic compounds. In particular, the dramatic reduction in conductivity represents a critical improvement in water quality with respect to its suitability for reuse in textile production processes.

When the RO effluent quality is evaluated in comparison with the international reference criteria presented in Table 3, it is observed that the parameters of pH, COD, conductivity, TSS, and color comply with both the reuse limits specified in the EU BREF document and the criteria defined in the technical specifications of the Ministry of Ecology and Environment of China. Similarly, when compared with the Class II criteria of the Turkish Surface Water Quality Regulation, the RO effluent quality remains below the relevant threshold values. In contrast, the effluents from the biological treatment and UF stages do not meet the reuse criteria, particularly in terms of conductivity and color.

These findings confirm that compliance with discharge standards does not necessarily guarantee reuse suitability, and demonstrate that hybrid membrane-based treatment systems are essential when water circularity is targeted rather than simple regulatory compliance.

Figure 2. Performance of the Treatment System in Terms of Key Water Quality Parameters

4. CONCLUSION

Textile production is among the most water-intensive industrial sectors, and particularly in denim manufacturing, processes such as dyeing, bleaching, and stone-washing generate wastewater with highly variable composition, elevated salinity, color, and suspended solids. These characteristics make textile effluents fundamentally different from many other industrial wastewaters and pose significant challenges for treatment and reuse.

The results of this study confirm that while conventional biological treatment is generally sufficient to achieve compliance with national discharge limits, it remains inadequate for process water reuse, particularly due to its limited ability to remove dissolved salts and residual color. The integration of advanced membrane processes, especially UF and RO, led to substantial improvements in all critical quality parameters. In particular, the pronounced reduction in conductivity and COD demonstrates that pressure-driven membrane systems play a decisive role in enabling water reuse in textile operations.

Although the dataset is based on a limited number of sampling campaigns and does not allow broad statistical generalization, the findings clearly indicate that discharge compliance alone does not ensure reuse suitability. For water-scarce regions, where freshwater availability directly affects industrial sustainability and operational continuity, hybrid treatment systems combining biological and advanced membrane processes represent not merely an environmental option but a strategic necessity.

In this context, shifting from discharge-oriented treatment design toward reuse-oriented system configuration emerges as a key requirement for achieving water circularity in the textile sector.

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