FINAL PROJECT REPORT

SAFECONOMY: Reinventing the Textile Circular Economy
A SMEP Project

An Advance Molecular Distortion Technique for Textile Wastewater Treatment and Solar Water Heating for Circular Economy

Project Number: APP00477

Project Duration: 24 months

FUNDING AGENCY

- The Foreign, Commonwealth & Development Office (FCDO) Under Sustainable Manufacturing and Environmental Pollution (SMEP)

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- Salt Separation Services, UK
- Access Group of Companies, Pakistan
- Sapphire Finishing Mills, Pakistan
- SE Drop, Pakistan

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

Textile sector is largest manufacturing sectors in Pakistan which employs fifteen million people and contributes 9% to its GDP (Alvi & Shahid, 2018; Shah et al., 2014). Pakistan is leading the export economy as it ranks 8^{th} in Asia for its textile goods and exported USD 14.83 billion worth textile (FF, 2025). Moreover, it has large production capacities of fiber and yarn of about 1048 and 9177.3 million m^2, respectively (Khan, 2025). Considering the large production, blue water footprint of textile finished product is around 169 m^3/ton (Naqvi et al., 2018). Consequently, nearly 0.83 billion m^3/year of wastewater is generated by textile sectors and out of which nearly 143 m^3/ton of finished textile (i.e., dyed and printed fabric) is discharged to water bodies (Maddah, 2025). Unfortunately, less than 8 % of the generated wastewater is being treated before disposal (Maddah, 2025). However, the wastewater rich in inorganic matter, dyes and salts is mainly due to chemical activities and 50 % of dyes are directly found in wastewater that impacted the water quality (Ahmed, 2011).

World Bank reported that almost 20% of water pollution is caused by the textile industry The textile effluent contains toxic chemicals, dyes, heavy metals, and physiochemical parameters such as BOD, TDS, pH, and COD that contaminate the ecosystem This untreated effluent causes diseases for humans and damages crops by reducing soil fertility (Sci et al., 2014). Therefore, the need for textile WW treatment becomes more crucial. The process of treating wastewater from textile industries in Pakistan is still relatively conventional and uses biological procedures like activated sludge, aerobic and anaerobic digestion and floating treatment wetlands (Ishfaq et al., 2025). These techniques do have certain drawbacks, though, especially when it comes to eliminating heavy metals, persistent organic contaminants and dyes from the effluent (Paździor et al., 2019).

In this regard, Molecular distortion techniques (MDTs) are emerging technologies to address these issues. MDTs degrade and destabilized the pollutants applying physical energy via extreme localized conditions like application of electric field (electro-coagulation), high temperature and pressure, radiations and sometimes producing highly reactive radicals/ions by oxidation process (Wang et al., 2022). While in advanced oxidation processes (AOPs) use some chemicals to destabilize pollutants and produce reactive (.OH) which degrade persistent pollutants. These techniques include methods like photolysis, plasma treatment, microwave-assisted oxidation, and ultrasonic irradiation, etc. (Parsons, 2004). Furthermore, the industry's shift to sustainable practices suffer by the lack of strict environmental rules and technology improvements (Zurek et al., 2021). To mitigate these challenges, international development programs are encouraging the transition to clean technologies in response to these challenges. For instance, United Kingdom initiates program like Sustainable Manufacturing and Environmental Pollution (SMEP) in Pakistan textile sector which is funded by UK and foreign aid (FCDO) programs. Moreover, the initiatives by SMEP like "Safeconomy – Reinventing the Textile Circular Economy" highlight the use of cutting-edge treatment methods such as Molecular Distortion Techniques (MDTs) including electrochemical oxidation process. In this context, the MDTs are used to improve the effectiveness of pollutant degradation that achieves approximately 98% pollutant removal with very high-water reuse to protect aquatic and human health.

2. Development of the textile wastewater treatment system

The FCDO (UK) generously funded a project titled “SAFECONOMY: Reinventing the Textile Circular Economy” under the SMEP Programme to develop modern textile wastewater treatment technology for the textile industry of Pakistan. The project is led by Northumbria University (UK) along with its partner institutions Bahauddin Zakariya University (Pakistan) and National Textile University (Pakistan), as well as industrial partner Access Engineering Pvt. Ltd., Lahore (Pakistan). The project research focuses on the development of an advanced molecular distortion technique (MDT) based textile wastewater system or MDT based SMEP system. The technology has the potential to provide environmentally friendly water pollutant removal solutions with minimal discharge of hazardous chemicals. This MDT based SMEP system has the potential to remove several hazardous pollutants from the textile wastewater.

2.1 Working principle of the system

The working principle of MDT technology is based on the molecular breakdown and oxidation of hazardous pollutants into simple and most reactive forms by the electrolysis process. These oxidized compounds are converted into a separable form and can be removed by skimming at the top and as sludge at the bottom. The schematic diagram and pictorial view of the MDT based textile wastewater treatment system developed in the SAFECONOMY project under the SMEP (FCDO) Programme are shown in Figure 1. The key components of the system are intake water suction pump, influent tank, reaction chamber, sand filter, micro filter, ultra-filter, and effluent tank. It is also equipped with TDS, pH, and temperature sensors to take the readings at various stages of treatment. Whole system operations are controlled by a digital central control panel. In addition, MDT based textile wastewater treatment system is integrated with solar water heating tubes for the reuse of treated wastewater. Water from the effluent tank is shifted to the heating tank with a pipe, and solar evacuated tube-heated water for further reuse in industry. Pictorial view of MDT based TWWT system integrated with solar evacuated water heating tubes is shown in Figure 2.

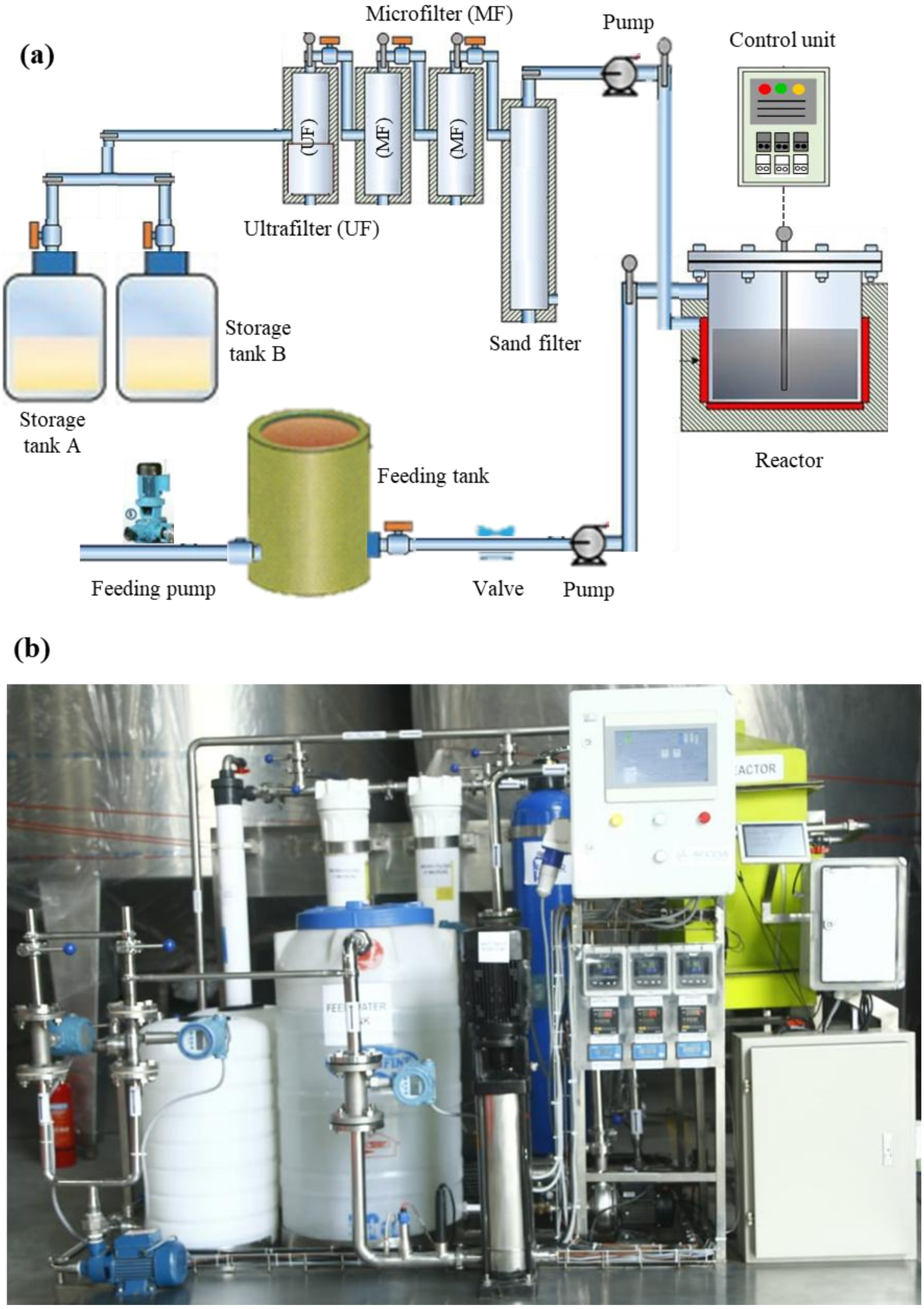

Figure 1 (a) Schematic diagram, and (b) Pictorial view of the MDT based textile wastewater treatment system developed in the SAFECONOMY project under the SMEP (FCDO) Program.

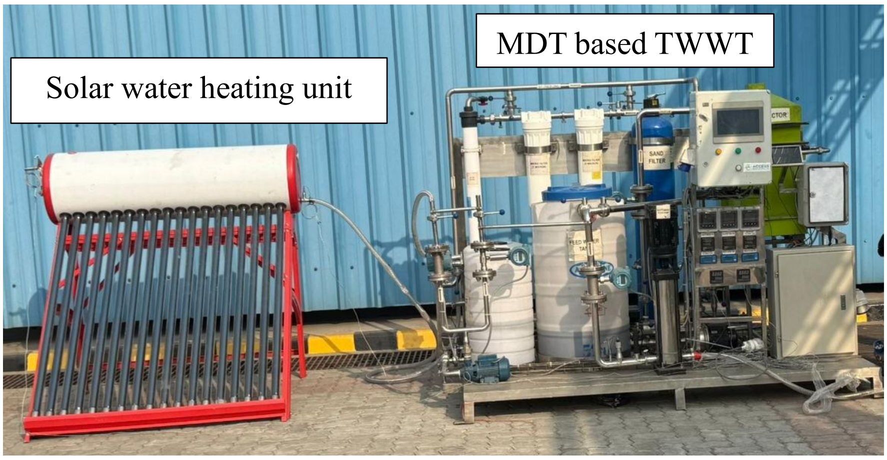

Figure 2 Pictorial view of MDT based SMEP system integrated with solar evacuated water heating tubes.

3. Experimental Results

A pilot-scale testing unit was installed at Sapphire Textile Finishing Mill Pvt. to assess and evaluate the system's performance using actual textile wastewater. The technical performance of the MDT based SMEP system has been assessed by considering the key parameters of wastewater quality standards like BOD, COD, TDS, TSS, heavy metals, phenol, sulfate, dyes and pigments, oil and grease, color, turbidity, and hardness. Water samples were collected from multiple wastewater streams, representing different pollutant loads, to assess treatment efficiency under diverse conditions. These variations allowed for a detailed analysis of system performance and reliability. Furthermore, the collected water samples were analysed in the laboratories of Sapphire, Bahauddin Zakariya University, and the National Textile University. Testing across multiple laboratories ensured the accuracy and reliability of the results. This approach strengthened the validation of the MDT-based system under varied operational and analytical conditions. Water sample collection and testing in the laboratory are shown in Figure 3 (a) and the status of textile wastewater before, during, and after coagulant formation is shown in Figure 3 (b).

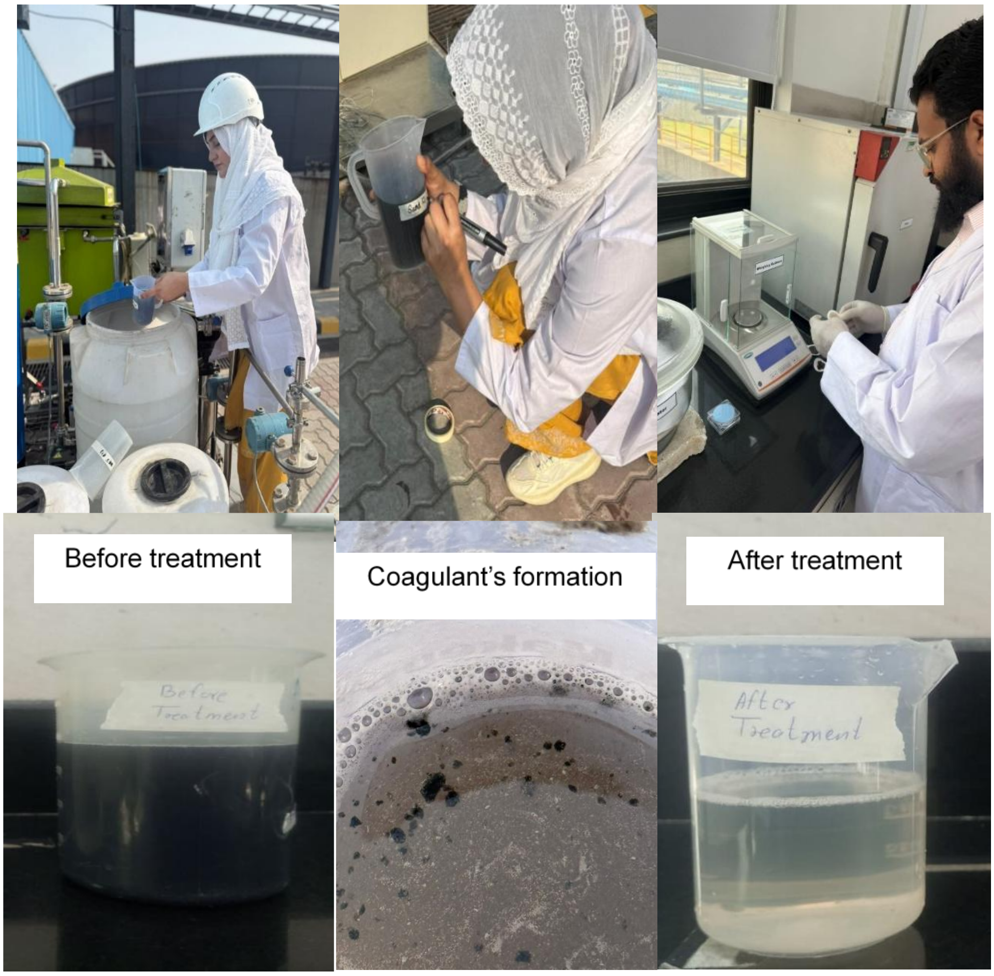

Figure 3 Textile wastewater sample collection and testing in the laboratory.

In the MDT based SMEP system, electrodes are installed inside the reactor to facilitate the degradation of pollutants. This process enables the transformation of complex textile contaminants into simpler and less harmful compounds. The electrodes used in this system are fabricated from different materials to evaluate their performance. In this study, three types of electrode materials were investigated: aluminum-based electrodes, mild steel-based electrodes, and stainless steel-based electrodes. Each type of electrode was applied separately for the treatment of textile wastewater, and their efficiencies were evaluated and compared to identify the most effective electrode material for pollutant removal. Each electrode type was tested using textile wastewater containing different concentrations of pollutants. The main objective was to evaluate and compare the effectiveness of these materials in achieving enhanced pollutant removal efficiency. Among the tested electrodes, aluminum based electrodes demonstrated the highest treatment efficiency, achieving removal efficiencies of up to approximately 90 % for heavy metals, as shown in Table 1. Mild steel based electrodes exhibited better performance than stainless steel based electrodes, showing comparatively higher pollutant removal efficiency. In contrast, stainless steel electrodes displayed relatively lower effectiveness among the tested electrodes. These findings highlight the importance of appropriate electrode material selection for improving the performance of the MDT based SMEP system.

Aluminium electrodes demonstrated removal efficiencies ranging from approximately 70 % to 90 % for various organic and inorganic pollutants in both Type-1 and Type-2 textile wastewater, as summarized in Tables 1 and Table 2, which present the pollutant removal performance of different electrode materials. These findings indicate that electrode material plays a significant role in the overall performance of the MDT-based system, with aluminium emerging as the most suitable option among the tested materials.

Table 1 Pollutant removal over time from Type-1 textile wastewater treated by mild steel, stainless steel, and aluminum based electrodes.

Time (min)	Mild Steel based electrode					Stainless Steel based electrode					Aluminum based electrode				
	TSS (ppm)	TDS (ppm)	Turbidity (NTU)	COD (ppm)	Heavy Metals Removal (%)	TSS (ppm)	TDS (ppm)	Turbidity (NTU)	COD (ppm)	Heavy Metals Removal (%)	TSS (ppm)	TDS (ppm)	Turbidity (NTU)	COD (ppm)	Heavy Metals Removal (%)
0	190	1590	123	3651	0	190	1590	123	3651	0	190	1590	123	3651	0
30	147	1420	102	3241	19	156	1479	109	3356	8	123	1380	70	2034	25
60	100	1338	89	2943	35	143	1380	95	2980	23	106	1250	50	1254	45
90	79	1197	72	2238	52	123	1249	72	2340	36	87	1249	38	743	60
120	63	1020	42	1632	65	109	1130	54	1720	49	57	1102	28	576	72
150	50	950	27	1190	75	87	993	34	1220	57	29	903	10	235	82
180	28	743	14	743	79	56	867	27	940	65	18	690	9	145	90

Table 2 Pollutant removal over time from Type-1 textile wastewater treated by mild steel, stainless steel, and aluminum based electrodes.

Time (min)	Mild Steel based electrode					Stainless Steel based electrode					Aluminum based electrode				
	TSS (ppm)	TDS (ppm)	Turbidity (NTU)	COD (ppm)	Heavy Metal Removal (%)	TSS (ppm)	TDS (ppm)	Turbidity (NTU)	COD (ppm)	Heavy Metal Removal (%)	TSS (ppm)	TDS (ppm)	Turbidity (NTU)	COD (ppm)	Heavy Metal Removal (%)
0	167	1676	106	3791	0	167	1676	106	3791	0	167	1676	106	3791	0
30	131	1320	94	3021	20	151	1435	89	3356	8	149	1356	97	2453	22
60	98	1290	67	2833	31	139	1309	95	2980	23	99	1120	86	1764	49
90	89	1130	59	2124	59	130	1124	72	2340	36	81	1080	58	1043	66
120	60	1020	45	1732	67	119	1100	54	1720	49	50	856	38	782	75
150	44	870	34	1090	78	87	929	34	1220	57	21	670	21	396	82
180	32	640	21	770	81	66	799	27	940	61	16	500	11	154	87

Based on the comparative experimental evaluation of different electrode materials, aluminum was identified as the most suitable electrode for subsequent investigations due to its superior treatment performance. Following this selection, a second phase of experimentation was conducted using aluminum electrodes at varying initial pollutant concentrations. This phase aimed to systematically evaluate the removal efficiency and overall performance of the MDT-based SMEP system under varying textile wastewater concentrations. The wastewater samples were categorized into low, medium, and high concentration ranges. For sample 1, the initial concentrations were 130 mg/L, 350 mg/L, 320 mg/L, and 3000 mg/L for BOD, COD, TSS, and TDS, respectively. The MDT-based system achieved removal efficiencies of approximately 98.88%, 98.85%, 95.93%, and 42.5% for BOD, COD, TSS, and TDS, respectively, within 120 minutes, as shown in Figure 4. Similarly, for Sample 2, the initial concentrations were 210 mg/L, 498 mg/L, 490 mg/L, and 3500 mg/L for BOD, COD, TSS, and TDS, respectively. After 80 minutes of treatment, the system removed about 95%, 95%, 97%, and 46% of BOD, COD, TSS, and TDS, respectively (Figure 5). In Sample 3, higher initial concentrations of 480 mg/L, 1200 mg/L, 600 mg/L, and 5000 mg/L for BOD, COD, TSS, and TDS were considered. After 120 minutes of treatment, the MDT-based system achieved removal efficiencies of approximately 93%, 93.4%, 99.1%, and 62.6% for BOD, COD, TSS, and TDS, respectively Figure 6.

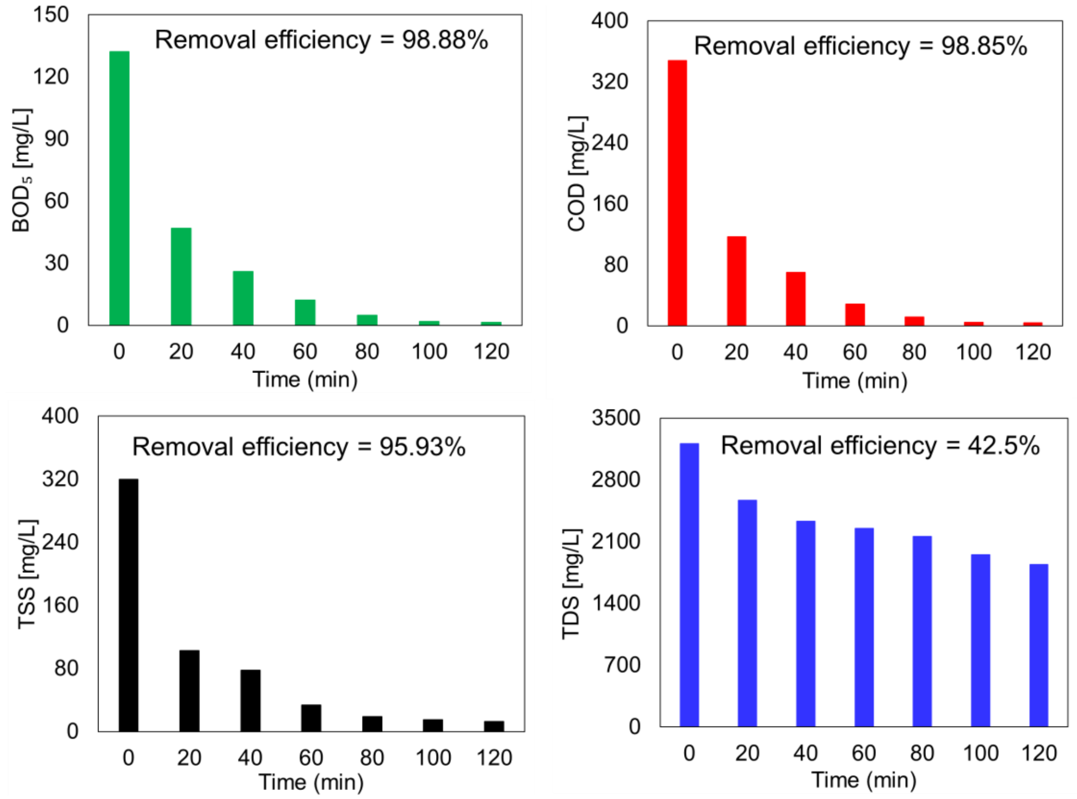

Figure 4 Temporal variation of BOD_5, COD, TSS, and TDS removal for textile wastewater sample 1 during the treatment process.

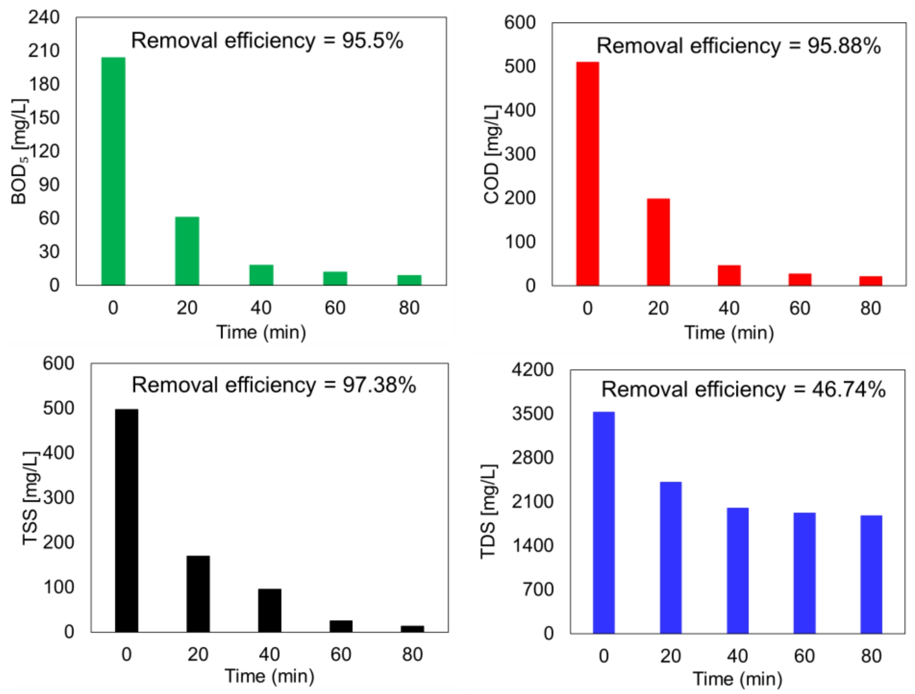

Figure 5 Temporal variation of BOD_5, COD, TSS, and TDS removal for textile wastewater sample 2 during the treatment process.

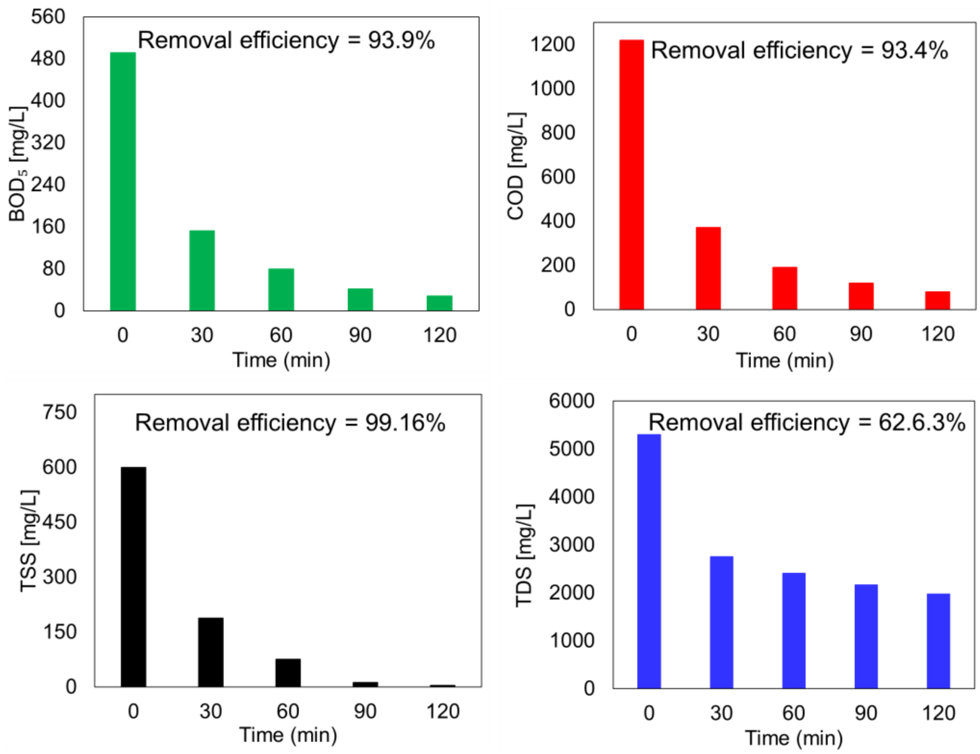

Figure 6 Temporal variation of BOD_5, COD, TSS, and TDS removal for textile wastewater sample 3 during the treatment process.

Figure 7 indicates a comparative evaluation of pollutant removal efficiencies [%] of the MDT based SMEP system and a conventional biological based system for various physicochemical parameters and heavy metals in textile wastewater. The results show that the MDT based SMEP system has achieved the removal efficiencies of approximately 92%, 90%, 60%, and 95% for BOD, COD, TSS, and TDS, respectively. In comparison, the biological-based conventional system demonstrated removal efficiencies of 85%, 70%, 20%, and 87% for the same parameters. Similarly, for heavy metals, the MDT-based SMEP system showed removal efficiencies of about 99% for Cr and 98–78% for Cr and As. In contrast, the biological-based conventional system was unable to remove these contaminants within acceptable limits or removed only negligible amounts. In the case of other pollutants such as phenol, sulphate, dyes and pigments, oil and grease, colour, turbidity, and hardness, the MDT-based system achieved removal efficiencies of up to 90–100%. These removal percentages were consistently higher than those observed for the biological based conventional system.

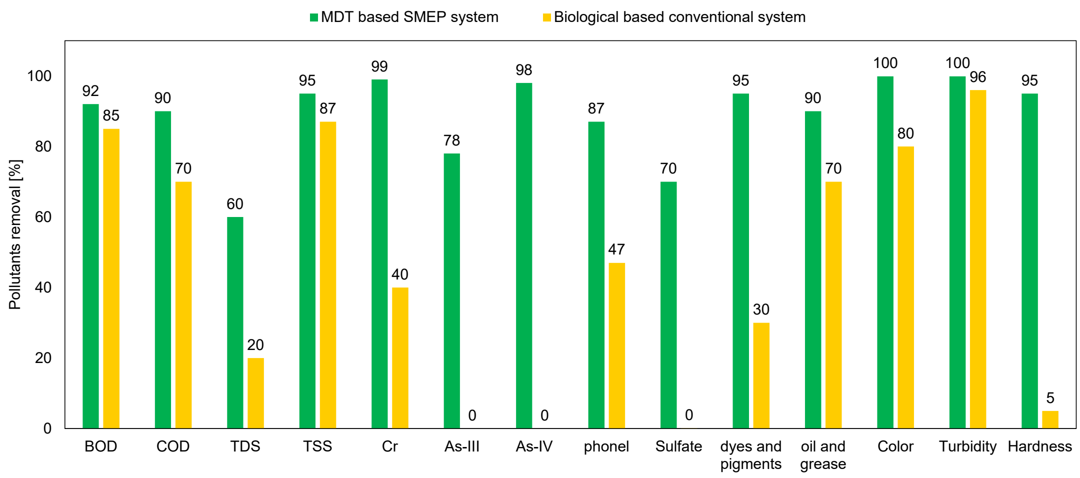

Figure 7 Comparative evaluation of pollutant removal efficiencies [%] of the MDT based SMEP system and a conventional biological based system for various physicochemical parameters and heavy metals in textile wastewater.

4. Simulation-Based Comparative Performance Evaluation of Conventional and Ozonation-Based Treatment Systems

The performance of two treatment configurations was evaluated through simulation using the GPS-X software(Fatima Akhtar, 2026). The first configuration (TS-1) represents a conventional biological treatment system, while the second (TS-2) incorporates an ozonation-based advanced treatment process. These simulations were conducted to compare their efficiency in removing key pollutants from textile wastewater under defined operational conditions.

4.1 Performance evaluation of biological based conventional treatment system (TS-1)

Textile wastewater is recognized for its high concentration of nitrogenous compounds, suspended solids, organic matter, and dyes. It is very difficult to treat highly concentrated textile wastewater using traditional biological systems. However, the performance of the biological based conventional treatment system (TS-1) for such wastewater is evaluated by GPS-X simulation. The treatment plant contains an equalization tank, primary clarifier, completely stirred flow reactor (CFSR), and secondary clarifier. The key parameters, such as COD, BOD, TKN, TOC, and TSS, were analyzed by the simulation for ten days of period using GPS-X.

According to the TS-1 results, the periodic changes of BOD are shown in Figure 8 for ten days of simulation. The BOD concentration in the primary clarifier dropped rapidly from 687 mg/L to 150 mg/L in the first half day, which demonstrates the quick destruction of biodegradable organic matter. There's a slight increase to 560 mg/L after 1.5 days due to transitional chemical accumulation or microbial adaptation. In CFSR, the BOD first decreases to 100 mg/L before stabilizing at 490 mg/L. To maintain constant effluent quality, the secondary clarifier further decreases BOD to less than 100 mg/L and remains steady during the simulation. Such patterns are aligned with research on conventional treatment systems that show the high BOD reduction is caused by initial microbial activity, and stabilization occurs as the system achieves steady-state results (Song et al., 2023).

In a similar pattern, COD results of the simulation for ten days show a clear pattern for each of the four treatment phases. As shown in Figure 9, the initial COD concentrations are reaching about 4800 mg/L in the primary clarifier (PC), 4000 mg/L in CFSR, and 3000 mg/L in the secondary clarifier (SC). In the first half day, the COD drops to about 2000 mg/L in PC, 1500 mg/L in CFSR, and 1000 mg/L in SC, which shows organic contaminants effectively removed at the initial stage. This is probably the result of sedimentation and microbial oxidation of easily biodegradable chemical compounds. After two days, there is a slight rise in CFSR due to the release of soluble microbial products and intermediates of deficient decomposition. The treatment system tends to reach a steady state after three days, which shows the stabilization of COD levels, which ends up at about 2200 mg/L in PC, 1800 mg/L in CFSR, and 1200 mg/L in SC.

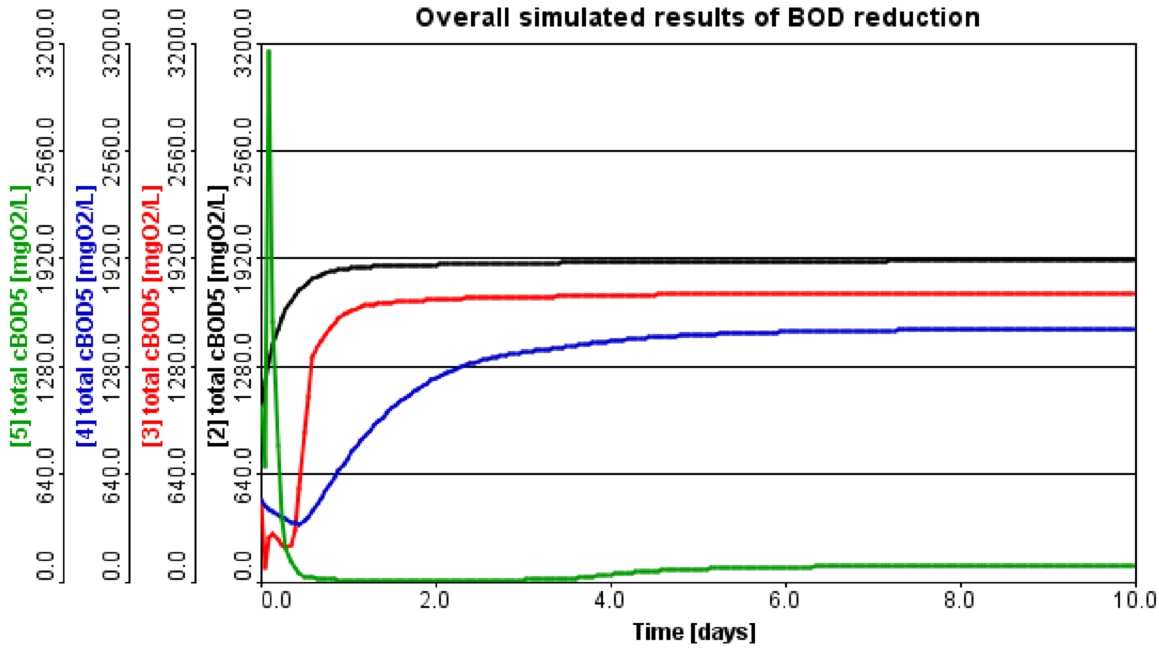

Figure 8 BOD reduction comparison of equalization tank, primary clarifier, CFSR, and secondary clarifier of conventional treatment system (TS-1).

These patterns are aligned with research on conventional treatment system that efficiently remove COD at first but there are some limitations due to their inability to break down complex textile organic compounds (Al-Tohamy et al., 2022). The concentration of total suspended solids (TSS) decreased in the first day from 2000 mg/L to less than 200 mg/L as shown in Figure 10. It stabilized at almost zero after that it indicates successful sedimentation and biomass retention.

However, Figure 11 shows simulation results of TKN reduction, indicating the quick and efficient removal of nitrogen. At different treatment stages, the initial TKN concentration is roughly 120 mg/L in the primary clarifier, 96 mg/L in CFSR, and 96 mg/L in the secondary clarifier. All three lines display a significant decrease during the first day, dropping to 0 mg/L in the primary clarifier, stabilized at 24 mg/L in the CFSR, and further dropped in the secondary clarifier. This indicates effective ammonification and nitrification processes. The final effluent shows TKN to zero over the next nine days, which indicates the total removal of nitrogen. Similarly, total organic carbon (TOC) reduction through this treatment system is shown in Figure 12. According to simulation results, TOC concentrations changed over time in the four treatment phases of equalization, primary clarifier, CFSR, and secondary clarifier.

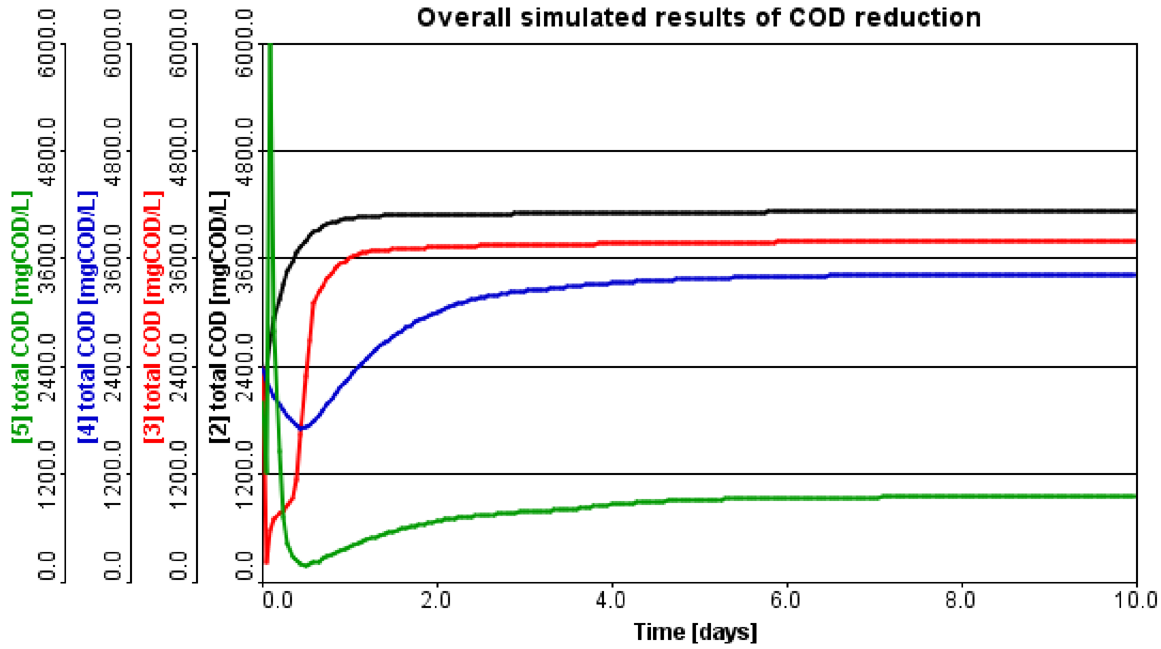

Figure 9 COD reduction comparison of the equalization tank, primary clarifier, CFSR, and secondary clarifier of the conventional treatment system (TS-1).

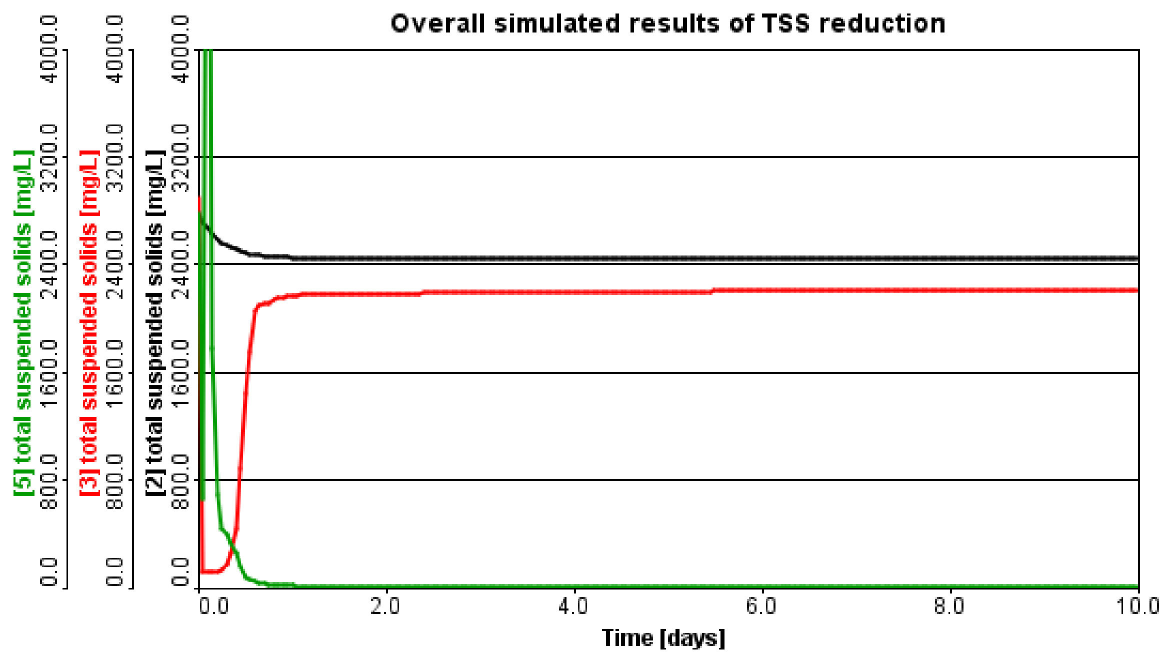

Figure 10 TSS reduction comparison of equalization tank, primary clarifier, CFSR, and secondary clarifier of conventional treatment system (TS-1).

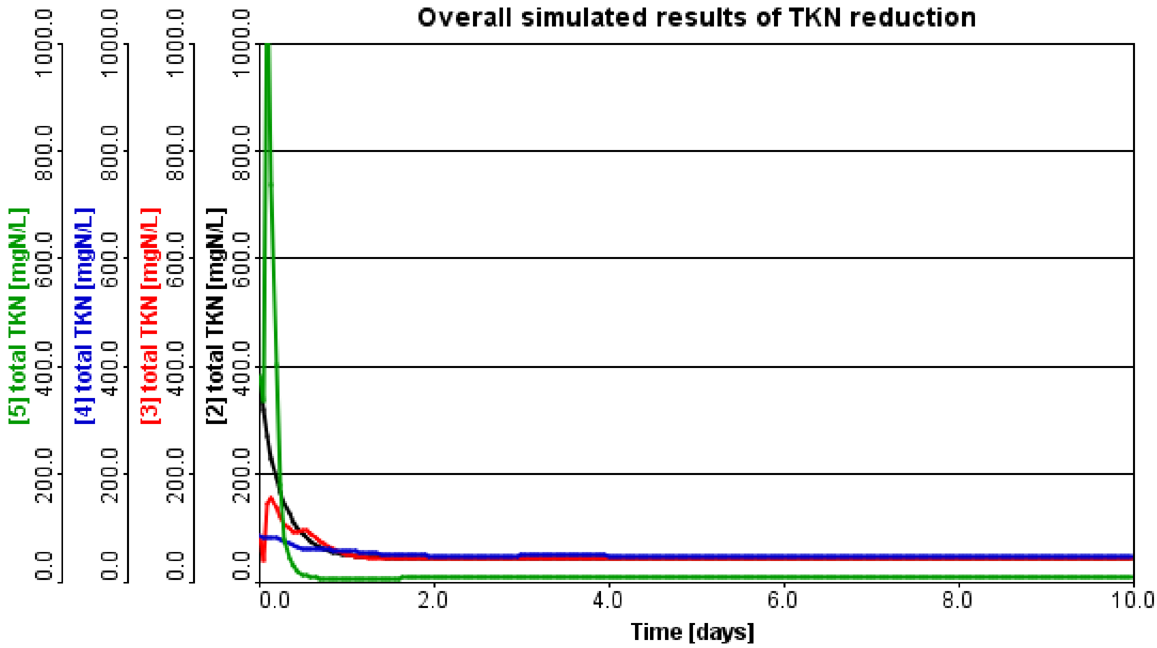

Figure 11 TKN reduction comparison of equalization tank, primary clarifier, CFSR, and secondary clarifier of conventional treatment system (TS-1).

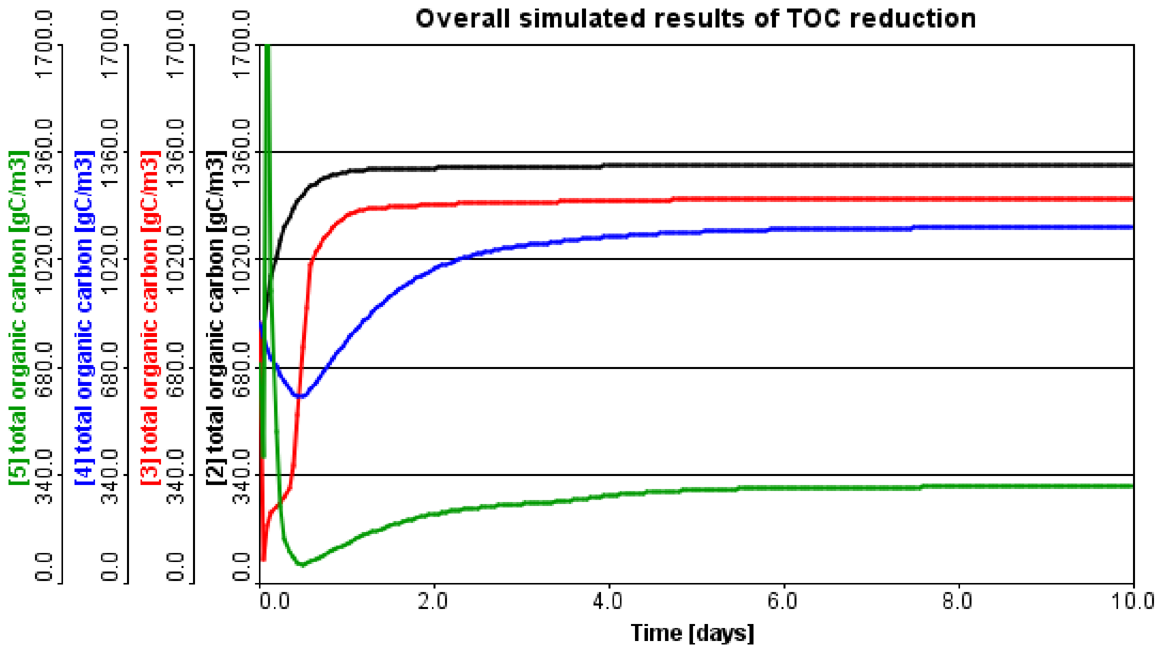

Figure 12 TOC reduction comparison of the equalization tank, primary clarifier, CFSR, and secondary clarifier of the conventional treatment system (TS-1).

Within the first 24 hours, TOC concentrations first decrease dramatically from around 1298 gC/m^3 to 124 gC/m^3 and early biological treatment effectively remove organic matter and suspended particles that are easily biodegradable as shown in Figure 6. Following this, TOC levels gradually rise and peak at about 216 gC/m³ by day 2 most likely because of the intermediate soluble organic molecules that are formed during microbial breakdown. From three to ten days, TOC concentrations stabilize and stay almost constant (~300 gC/m³) following this brief increase, indicating that the system has achieved dynamic equilibrium. This behavior is consistent with literature that shows the conventional system first reduces TOC rapidly before stabilizing as a result of microbial adaptation and steady-state operation. Furthermore, Table 3 provides an overview of COD, BOD, TKN, TSS, and TOC reduction at different units of TS-1. The results show that secondary clarifier achieves effective pollutant removal. The patterns show that TS-1 works well with moderate organic loads. However, it might not be sufficient for textile wastewater with high COD.

Table 3 Performance evaluation summary of pollutant reduction at each treatment unit of TS-1.

Treatment plant	**Flow** (m^3/d)	**BOD_5** (mgO_2/L)	**COD** **(mgO2/L)**	**TSS** (mg/L)	**TKN** (mgN/L)	**TOC** (mgC/L)
Influent	5000	1869	4056	2404	42	1298
Equalization tank	5010	1907	4122	2453	42.005	1319
Primary clarifier	4960	1716	3790	2207	41.97	1213
CFSR	5000	1500	3426	2074	46.97	1122
Secondary clarifier	3960	94	944	7.64	9.013	303

4.2 Performance Evaluation of Ozonation-based Treatment System (TS-2)

Ozonation-based treatment plant (TS-2) is an improved textile treatment system that overcomes the limitations of conventional treatment system for high strength organic and nitrogenous compounds. The treatment train of TS-2 consists of setup units of an equalization tank, primary clarifier, CFSR, secondary clarifier, ozonation tank, and membrane filtration. Ozonation-based process decomposes complex organic compounds while membrane filtration purified/cleaned the final effluent. The simulation of ten days conducted for this system using GPS-X and assessed the reduction of BOD, COD, TSS, TKN, and TOC through the whole process.

According to simulation results, Figure 13 represents that BOD concentration at primary clarifier initially high about 600 mg/L. In the first half day, it drops to about 150 mg/L in CFSR, and 80 mg/L in secondary clarifier. The CFSR shows a small rise in BOD from day 1 to day 3 due to the breakdown of intermediate organics of soluble microbial compounds during active biological degradation. It is further reduced to about 20 mg/L by the ozonation tank and nearly removed by membrane filtration units that gives the final effluent BOD levels below 5 mg/L. These results coincide with research on membrane technologies and AOPs which combined biological treatment and reported >95% results of BOD removal (xiangyu et al., 2025). The system attains hydraulic and biological stability with minimal changes after three days. The results show that such treatment system is resilient and treats highly concentrated BOD wastewater and discharges the effluent according to the standards.

COD is effectively reduced by the advanced treatment unit, as shown in Figure 14. Initial COD concentrations range from roughly 4800 mg/L in the equalization tank to 3000 mg/L in the primary clarifier. In the first 2 days, there is a noticeable drop in COD from 4800 mg/L to 1500 mg/L in the primary clarifier and from 3000 mg/L to 800 mg/L in the secondary clarifier. This quick reduction is due to improved biological oxidation in CFSR, an efficient primary clarifier, and oxidative degradation through ozonation (Qi et al., 2011). COD concentrations initially decreased in 2 days, and in 5 days, it dropped to <100 mg COD/L. After that the effluent level stabilizes and indicates overall successful treatment. The scientific literature on AOPs and integrated biological treatments reports the COD reduction above 95% in textile wastewater treatment (Nadeem et al., 2017). This coincides with more than 97% COD removal effectiveness.

Moreover, TSS removal is very effective in this treatment system. As shown in Figure 15, the primary clarifier and secondary clarifier majorly remove TSS, bringing the initial concentration of 2000 mg/L to less than 10 mg/L of final effluents concentration. The membrane filtration ensured that the remaining solids were completely removed. After three days, the system stabilizes and maintains low TSS levels and generates good quality effluent for discharge or reuse. However, TKN simulation results show that nitrogen is removed quite effectively during the treatment, as shown in Figure 16. The range of initial TKN concentrations is roughly 120 mgN/L to 96 mgN/L. During the first two days, a dramatic decrease in all treatment units stabilized at 20 to 25 mgN/L and fell to about 5 mgN/L by ozonation tank. A similar pattern shows the steady performance throughout the treatment units. Such rapid reduction is a result of effective ammonification and nitrification methods that are improved by ozonation and membrane filtration (Ma et al., 2024). After three days, the system has achieved a steady state when TKN levels are constant.

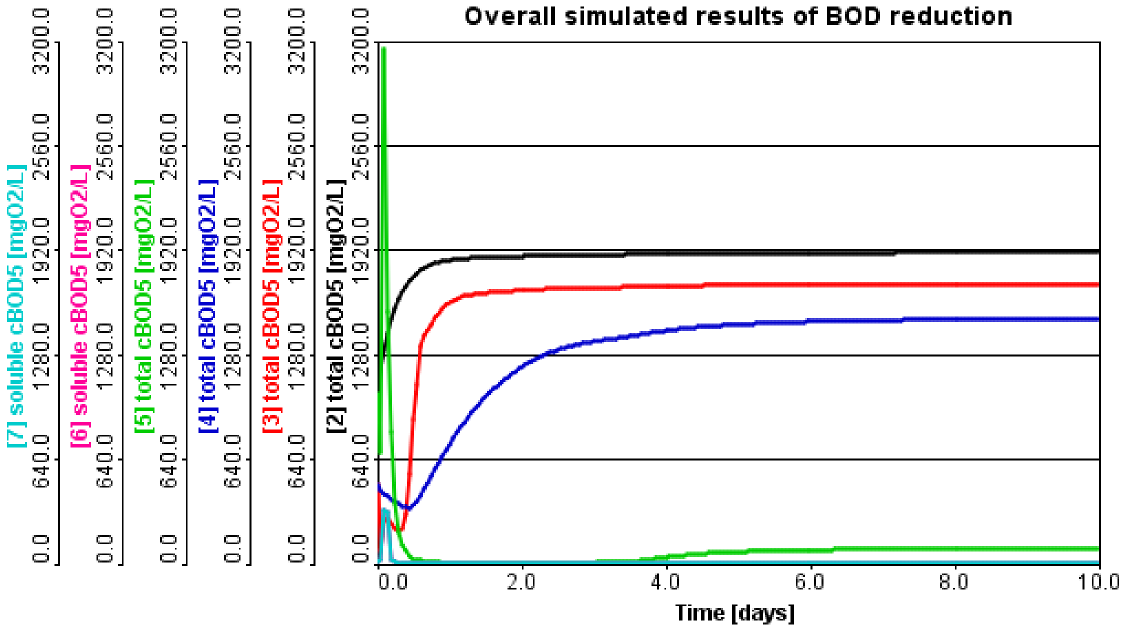

Figure 13 BOD reduction comparison of equalization tank, primary clarifier, CFSR, and secondary clarifier, ozonation tank, and membrane filtration of ozonation-based treatment system (TS-2).

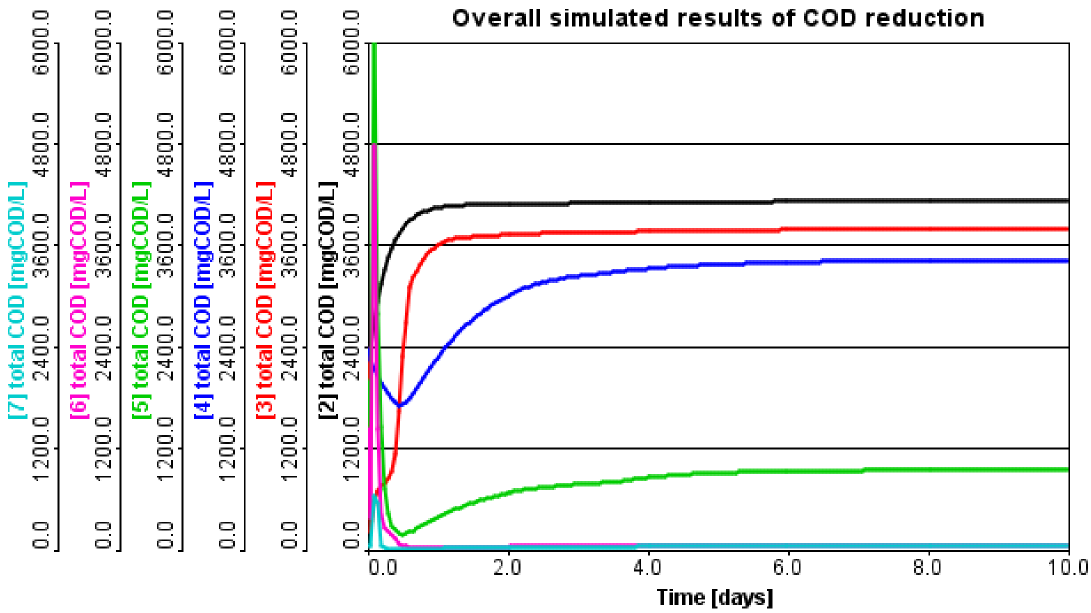

Figure 14 COD reduction comparison of equalization tank, primary clarifier, CFSR, and secondary clarifier, ozonation tank, and membrane filtration of ozonation-based treatment system (TS-2).

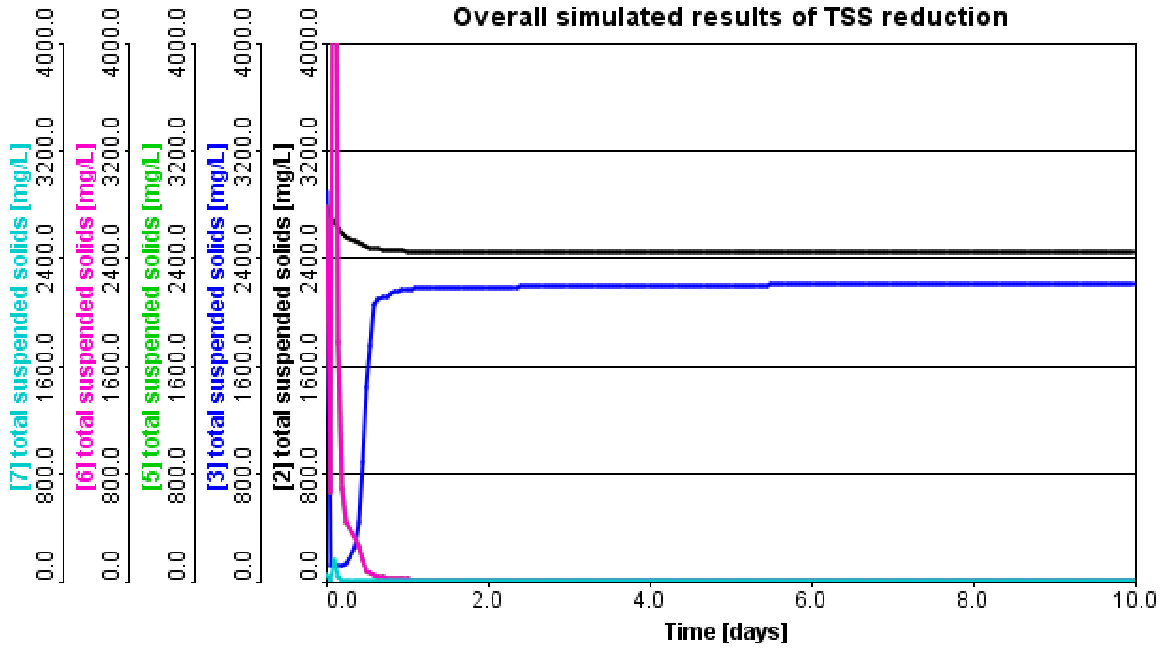

Figure 15 TSS reduction comparison of equalization tank, primary clarifier, CFSR, and secondary clarifier, ozonation tank, and membrane filtration of ozonation-based treatment system (TS-2).

However, total organic carbon (TOC) reduction through this system, as shown in Figure 17, indicates that organic carbon is removed very effectively at each treatment unit. In the first half-day, TOC decreases significantly from around 1298 gC/m³ to about 19.5 gC/m³, mostly because of biological and physical processes in the equalization tank, primary clarifier, and CFSR. After that, there is a minor recovery with TOC increasing to about 207 gC/m³ by day 2 as a result of complex organics being broken down by microbes into soluble intermediates. Later phases, such as secondary clarifier, ozonation tank, and membrane filtration, gradually decrease TOC until the final effluent stabilizes at about 15 gC/m³ by day three and stays that way until day ten. It shows how physical separation and oxidative degradation can increase removal efficiency. Particularly when COD loading is high, this pattern shows that ozonation and membrane filtration greatly outperform the conventional system in TOC reduction, as supported by the literature. Therefore, TS-2 performs better than TS-1, which attains low and consistent TOC levels appropriate for reuse or discharge.

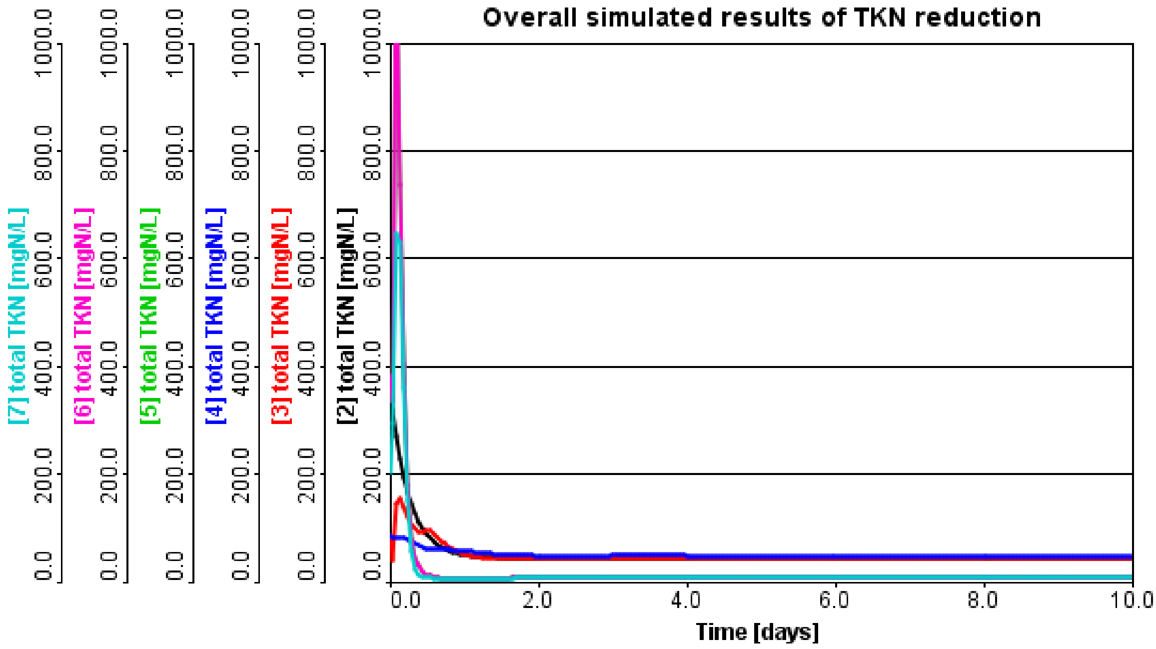

Figure 16 TKN reduction comparison of equalization tank, primary clarifier, CFSR, and secondary clarifier, ozonation tank, and membrane filtration of ozonation-based treatment system (TS-2).

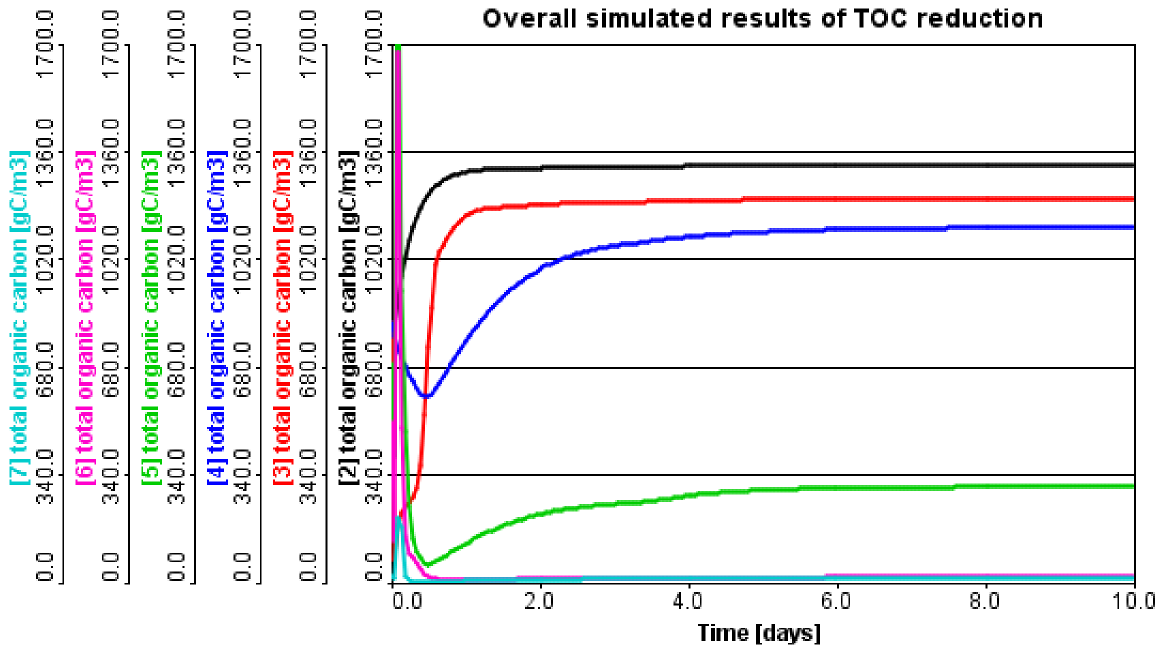

Figure 17 TOC reduction comparison of equalization tank, primary clarifier, CFSR, and secondary clarifier, ozonation tank, and membrane filtration of ozonation-based treatment system (TS-2).

Moreover, Table 4 provides an overview of COD, BOD, TKN, TSS, and TOC reduction at different units of TS-2. The pattern shows that TS-2 works well with high organic loads for textile wastewater with high COD. The result provides a well-organized treatment strategy where ozonation tank and membrane filtration increase the overall effectiveness of pollutant removal.

Table 4 Performance evaluation summary of pollutant reduction at each treatment unit of TS-2.

Treatment plant	**Flow** (m^3/d)	**BOD$_5$** (mgO_2/L)	**COD** **(mgO2/L)**	**TSS** (mg/L)	**TKN** (mgN/L)	**TOC** (mgC/L)
Influent	5000	1869	4056	2404	42	1298
Equilization tank	5010	1907	4122	2453	42.005	1319
Primary clarifier	4960	1716	3790	2207	41.97	1213
CFSR	5000	1500	3426	2075	46.97	1122
Secondary clarifier	3960	94	944	7.64	9.013	303
Ozonation tank	3960	9.64	56	7.64	9.013	18
Membrane filtration	3959	4.55	47	0.152	8.87	15

5. Assessment of the technical performance of MDTs

The high percentage removal achieved by the MDT-based system also contributed to a significant reduction in pollutant load entering natural waterways, as fewer contaminants were discharged directly into receiving water bodies. Effective treatment of wastewater through MDT based system can reduce the annual discharge of various pollutants approximately 30.542 kt/year of BOD, 354.38 kt/year of COD, and 19.87 kt/year of TSS into natural streams. In addition, the MDT based system can reduce the discharge of heavy metals, including about 0.28 kt/year of As and 2.124 kt/year of Cr, in the water bodies, thereby minimizing their environmental impact. Similarly, the pollutant loads of other contaminants, such as phenol and sulphate, are also reduced as a result of improved treatment efficiency, as shown in Figure 18. Overall, the enhanced removal performance of the MDT-based system demonstrates its potential to substantially restrict the contamination burden on receiving water bodies and contribute to improved environmental protection.

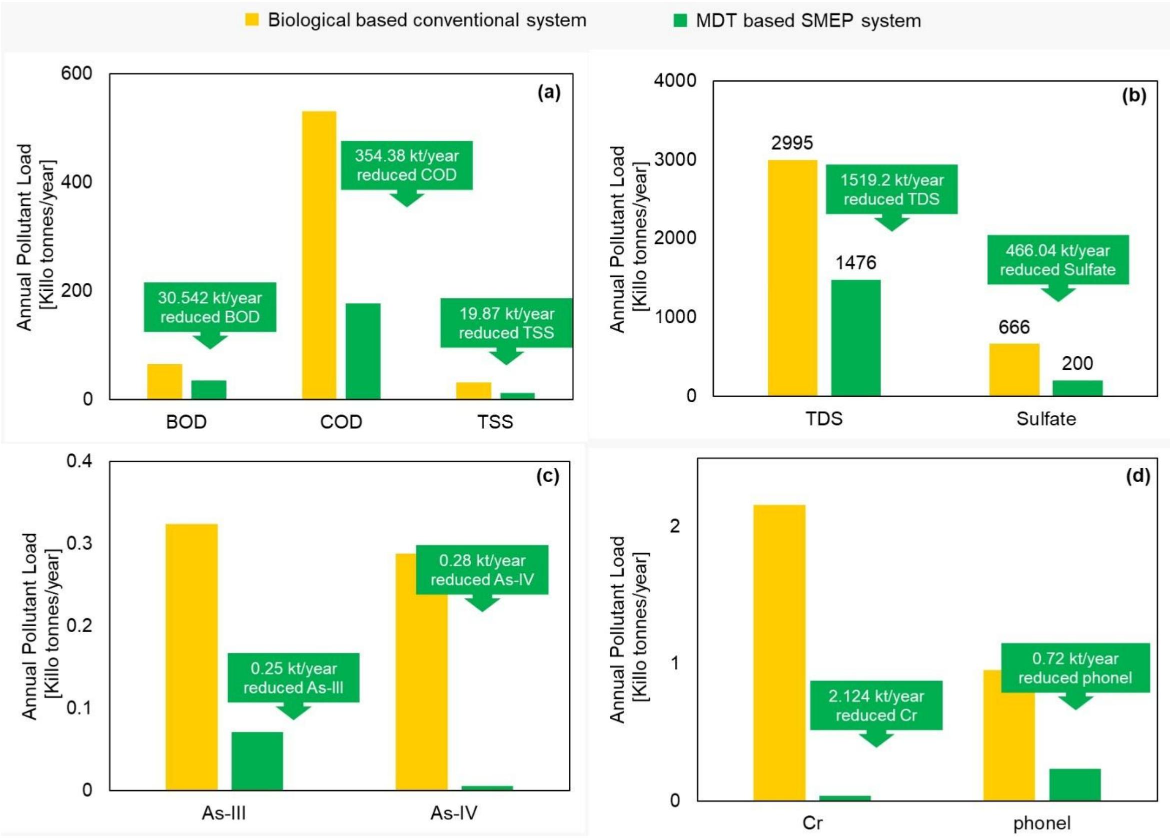

Figure 18 Annual reduction in pollutant load entering the water bodies (a) BOD, COD, and TSS, (b) TDS and Sulfate, (c) As-III and As-IV, (d) Cr and Phenol.

5.1 Energy requirements

The energy requirement for the treatment per cubic meter of wastewater is also reduced in comparison with biological based conventional system. Typically, complete biological treatment processes require about 2 kWh of energy to treat 1 m^3 of wastewater. However, in the case of the MDT-based system, the total energy requirement is approximately 1.08 kWh per cubic meter, representing an energy saving of about 45.8%, as represented in Figure 19 (a). Similarly, when considered this figure on an annual basis, this reduction translates into an estimated saving of approximately 662 million kWh of energy as shown in Figure 19 (b).

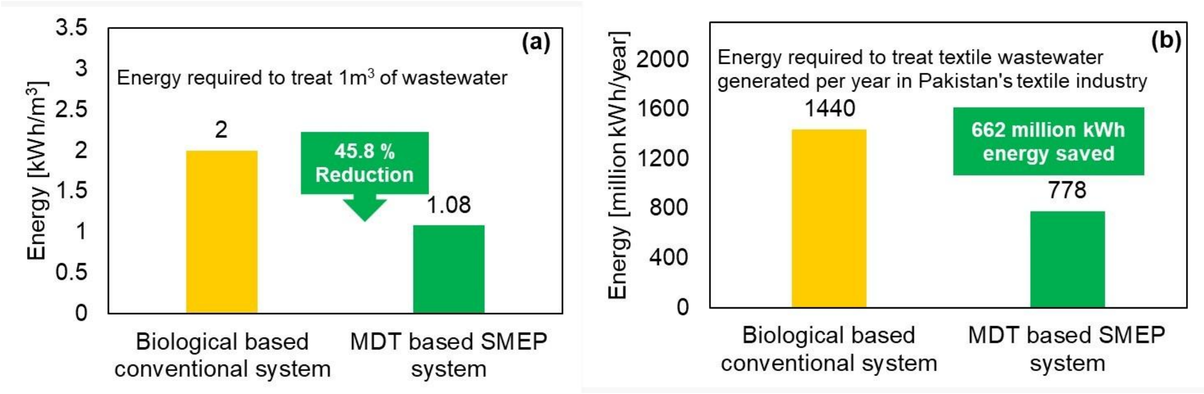

Figure 19 Energy required to run the system (a) energy required to treat 1m^3 of water (b) annual energy savings.

5.2 Water recovery and reuse

The MDT-based system has about 70% water recovery after treatment, which can be reused in various operations within textile industries. In this way, the reuse of treated wastewater not only reduced freshwater demand but also contributed to improved resource efficiency in industrial operations. Since textile processing requires large volumes of water, this recovery significantly lowers the pressure on available water resources. An additional benefit of reusing treated water is the reduction in energy required for heating. The temperature of the recovered water is already about 7–10 °C higher than normal temperature water, which decreases the amount of heat needed for boiling or heating of water before use in industrial processes. In this way, approximately 64% less heat energy is required to raise the temperature of the recovered water to operational levels, as shown in Figure 20 (a). This reduction in heating demand leads to considerable energy savings in textile industries. In terms of overall energy consumption, the reuse of treated water through the MDT-based system results in an estimated annual saving of about 42 million kWh, as shown in Figure 20 (b).

In addition to the energy savings in treatment processes and heating of water, the MDT-based system also significantly reduces the energy required for water pumping. Since approximately 70% of the treated water is recovered and reused within the system, the need for pumping fresh water from external sources is greatly reduced. This leads to a reduction in pumping energy by about 65–70%, as presented in Figure 21. In practical terms, this results in an annual energy saving of approximately 175 million kWh solely from reduced pumping requirements.

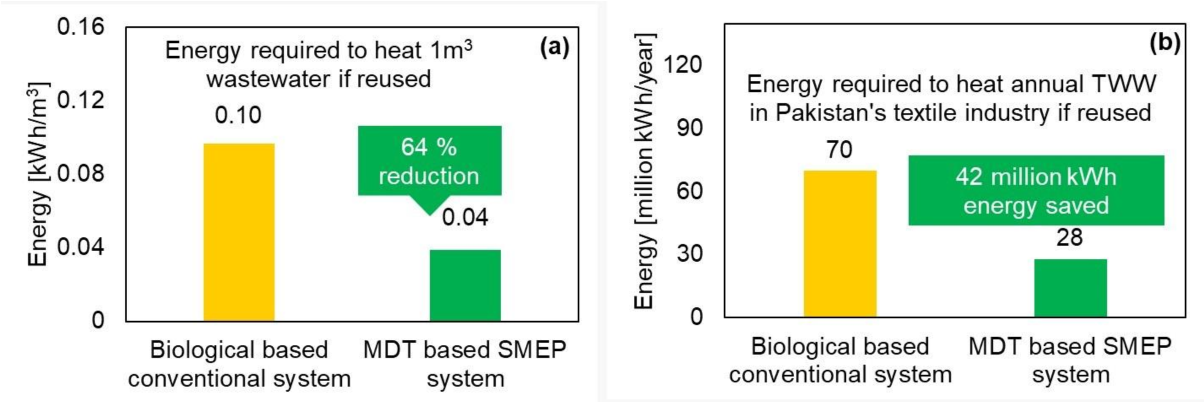

Figure 20 Energy required to heat the water if reused after treatment (a) energy required to heat 1m^3 of water (b) annual energy savings for heating.

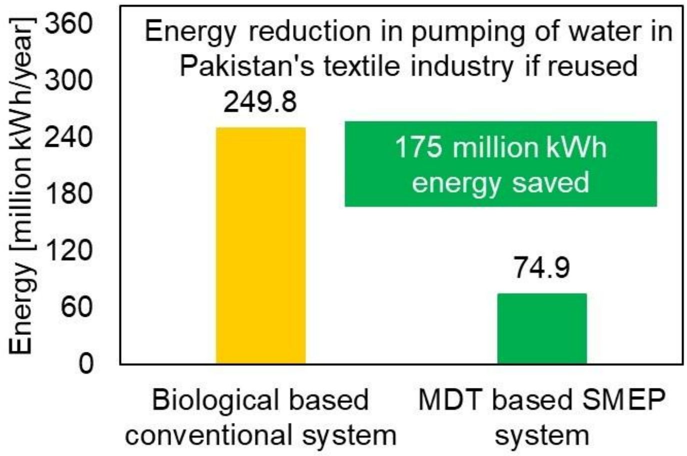

Figure 21 Energy required to pump the groundwater to use in industries.

These energy savings not only reduce energy demands but also contribute to lowering carbon emissions associated with energy generation. About 33.5 g of CO2 and 9.2 g of carbon are emitted in the environment for the treatment of 1m3 of wastewater if treated with a biological-based conventional system. However, in the case of MDT based system its only 4.7 g of CO2 and 1.3 g of carbon emitted, which is 86.01% is less than conventional systems, as shown in Figure 22 (a). When converting these savings on an annual basis, about 20,770 tonnes of CO2 emissions are reduced, similarly, 5,712 tonnes of carbon emissions are reduced as given in Figure 22 (b).

Such significant energy savings are particularly important for developing countries like Pakistan, which are already facing energy shortages. Therefore, the implementation of MDT-based systems can serve as an effective option to reduce energy demand while improving wastewater treatment efficiency.

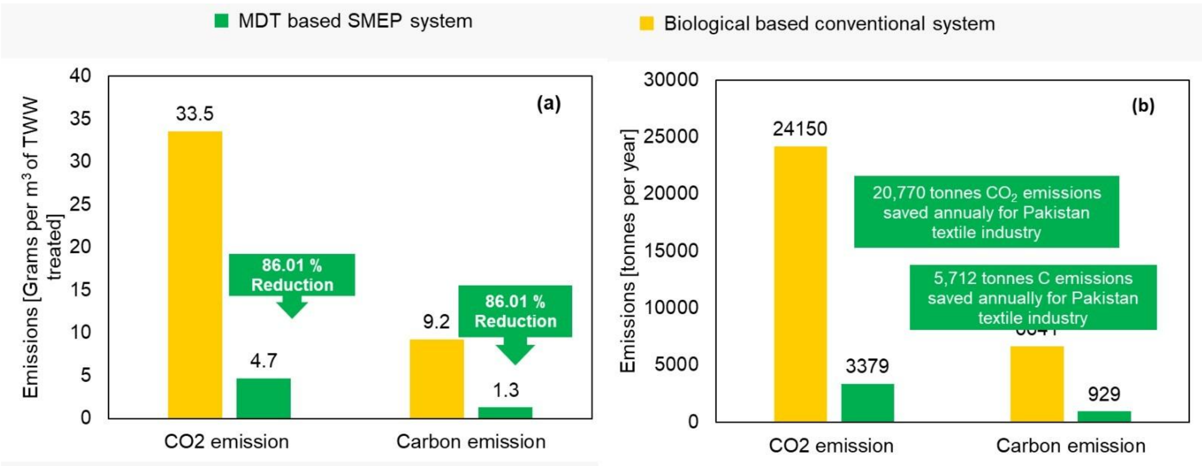

Figure 22 CO_2 and carbon emission (a) for treatment of 1m^3 of water (b) annual reduction.

5.3 Time, cost, and chemical usage impacts

Biological based system requires more time to treat 1m^3 of wastewater compared to MDT based system because bacterial need more time to start their activities. Usually, a biological system requires about 7 to 12 days for complete treatment of water but MDT required maximum 2 to 3 hrs for complete treatment as shown in Figure 23.

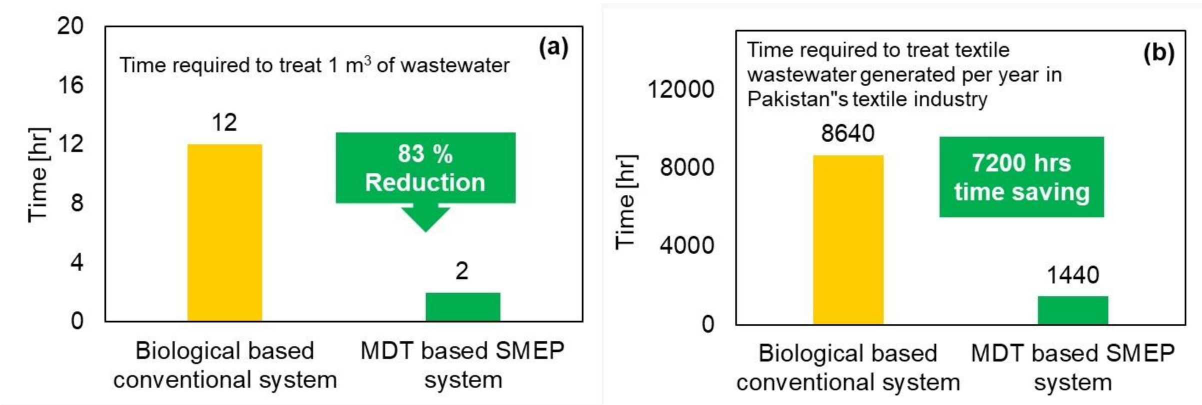

Figure 23 Time for treatment of water biological based system vs MDT based system (a) for treatment of 1m^3 of water, (b) annual time savings.

Biological based conventional systems require multi-stage chemical interventions, which produce significant operational and environmental burdens. For example, the coagulation and flocculation processes require about 500 g/m^3 of coagulants like alum, ferric oxides, and polymers. Similarly, at different stages of the treatment process for pH balance, caustic soda or sulfuric acid is used, and for process enhancement, nutrients are added, as shown in Figure 24 (a). A huge amount of these chemicals is required to properly treat the wastewater as shown in Figure 24 (b). These additives generated the complex biosolids and toxic sludge, which are not easy to handle and dispose of. The addition of these chemicals impacts the environmental footprint in various ways, such as high energy consumption during manufacturing and transport, the generation of chemical byproducts into sludge, and a significant increase in the cost of wastewater treatment. However, in the case of MDT based system that operates as a chemical-free or low-chemical alternative, which eliminates the need of chemical for primary and secondary processes. In this way, MDT based system not only reduces the treatment cost but also mitigates the environmental loading associated with traditional chemical manufacturing and sludge management. In addition to energy savings and reduced carbon emissions, the MDT-based system also offers significantly lower operational costs due to minimal or negligible use of chemicals. In conventional biological treatment systems, the cost of treating 1m^3 of wastewater is approximately 1.44 USD, whereas the MDT-based system requires only about 0.41 USD per cubic meter. This represents a cost reduction of approximately 71.28%, as shown in Figure 25 (a). When scaled to annual operations, this cost efficiency translates into an estimated savings of around 741.6 million USD, as illustrated in Figure 25 (b). The combination of lower chemical consumption, reduced energy requirements, and overall operational efficiency makes the MDT-based system not only an environmentally sustainable solution but also a highly cost-effective option for textile wastewater treatment. In addition, conventional biological treatment systems require multiple stages, including primary treatment, the main reactor, and post-treatment units, which collectively demand a large area for installation and operation. In contrast, the MDT-based system combined all treatment processes within a single main reactor, eliminating the need for separate treatment stages. As a result, the MDT-based system requires approximately 80.7% less land for operation compared to conventional systems, as shown in Figure 26. This compact design not only reduces the physical footprint of the treatment facility but also lowers associated infrastructure and maintenance costs, making it a more efficient and space-saving solution for industrial wastewater management.

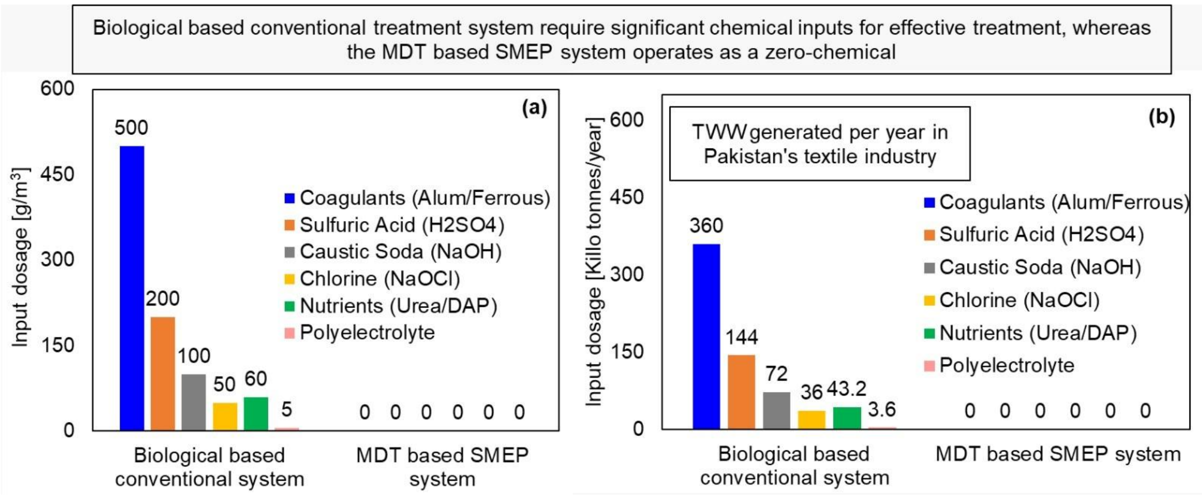

Figure 24 Use of chemicals in various processes for the treatment of wastewater.

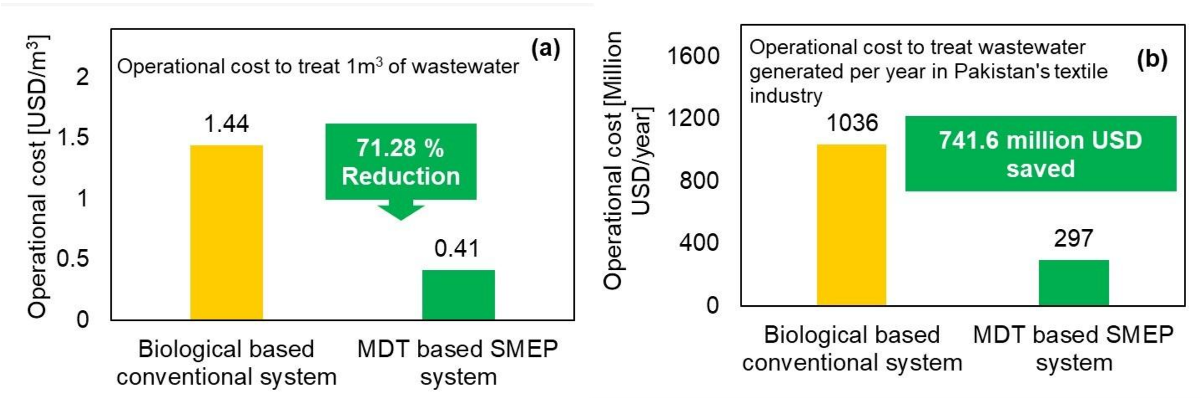

Figure 25 Operational cost comparison (a) for treatment of $1m^3$ of water (b) annual cost saving.

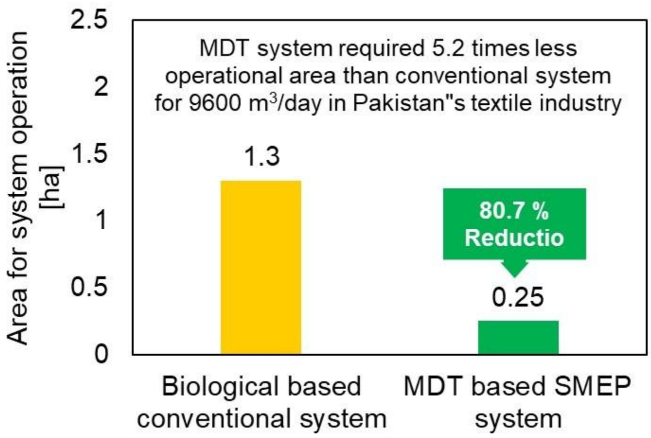

Figure 26 Area required for wastewater treatment systems.

5.4 Gender equality and social inclusion (GESI) analysis

In Pakistan, a large workforce is associated with the textile industry, making it one of the country's most significant employment sectors. Approximately 15 million laborers are engaged in the textile sector, of which about 30% are women. Among these women workers, only 12% are employed in industries that provide a safe working environment and properly follow standard operating procedures (SOPs). The safety status of approximately 33% of women workers remains unclear, making it difficult to determine whether they are working in safe or hazardous conditions. Alarmingly, around 55% of women are considered to be at risk due to exposure to unsafe working environments as shown in Figure 27.

This situation indicates that a large proportion of women employed in the textile sector face potential occupational health and safety risks, particularly due to inadequate wastewater treatment and improper disposal practices. Exposure to untreated or poorly treated textile effluents can adversely affect worker health and environmental conditions around industrial sites. The proper installation and implementation of MDT-based treatment systems can significantly improve compliance with safe disposal standards. Consequently, this would contribute to safer working environments, enhance occupational health protection, and improve job security for women working in the textile sector.

Figure 27 GESI analysis of the job security of women in the Pakistan textile industry.

6. Compliance with national and international standards

Textile wastewater contains a wide range of toxic pollutants, including heavy metals, dyes, toxic radicals, and various chemical compounds. These contaminants pose significant challenges for treatment, particularly when conventional biological methods are employed, as biological treatment systems rely on microbial activity, which can be adversely affected by the presence of toxic substances. Heavy metals such as Cr and As are particularly more harmful for microbial growth and activity, and cause their death. Therefore, biological based conventional system often fails to remove these pollutants effectively. In contrast, the MDT based system showed a high ability to remove heavy metals and toxic pollutants. Pollutant concentration after treatment of MDT based system is compared with Zero Discharge of Hazardous Chemicals (ZDHC) (ZDHC Wastewater, 2024), National Environmental Quality Standards (NEQs), Pakistan, (Pakistan Environment Protection Agency October 1997 Sectoral Guidelines for Environmental Reports-Major Chemical and Manufacturing Plants, n.d.) and Agriculture reuse FAO/WHO standards (A Compendium of Standards for Wastewater Reuse in the Eastern Mediterranean Region, 2006) . it is inferred that the concentration of mostly pollutants like BOD, COD, TSS, TDS, and oil and grease are within the limits of national and international standards, as shown in Table 5. However, in the case of biological based conventional system, most of the pollutants like phenol, sulfate, and TDS are not in the permissible limits of safe discharge.

Table 5 Comparison of results with National/International Standards (A Compendium of Standards for Wastewater Reuse in the Eastern Mediterranean Region, 2006; Pakistan Environment Protection Agency October 1997 Sectoral Guidelines for Environmental Reports-Major Chemical and Manufacturing Plants, n.d.; ZDHC Wastewater, 2024).

Parameters	ZDHC	Pakistan NEQS	Agriculture Reuse (FAO / WHO)	TWW (Before Treatment)	After Treatment	
					Biological based conventional system	MDT based SMEP system
Cr	≤ 0.2	-	≤ 0.02	5	3	0.05
As	≤ 0.05	≤ 1.0	≤ 0.05	0.4	0.4	0.099
Phenol	≤ 0.5	≤ 0.1	≤ 0.002	2.5	1.3	0.32
Sulphate	-	≤ 600	≤ 400	926	925	278
oil and grease	≤ 10	≤ 10	≤ 8	56	16.8	5.6
pH	6.0 – 9.0	6.0 – 9.0	6.5 – 8.5	8.32 – 8.85	8.5	8.43
BOD_5 (mg/L)	≤ 30	≤ 80	≤ 30	60 – 120	91	28
COD (mg/L)	≤ 150	≤ 150	≤ 50–100 (depending on crop)	148 – 320	738	80
TSS (mg/L)	≤ 50	≤ 150	≤ 50	120 –629	45	5
TDS (mg/L)	-	≤ 3,500	≤ 2,000	2700 – 3980	3500	1930

Colour (436; 525; 620)	7; 5; 3	-	-	30.6; 24.5; 19.9	-	3.91; 2.55; 1.91

7. Technical Limitations and Recommendations

7.1 Electrical Connection Reliability and System Integrity

Loose or improper electrical connections can increase resistance, resulting in overheating, energy losses, and potential damage to system components; therefore, it is recommended to use copper wiring with stainless steel or brass terminals to ensure high electrical conductivity. Additionally, all connections should be properly tightened, equipped with vibration-resistant fittings, and subjected to regular inspection and maintenance to ensure system reliability and safety.

7.2 Electrode Passivation and Surface Fouling

The formation of non-conductive layers on electrode surfaces reduces current efficiency and overall treatment performance; therefore, it is recommended to implement regular polarity reversal and utilize high-quality electrode materials to minimize fouling. Aluminium electrodes offer high pollutant removal efficiency due to their strong coagulation properties, although they are more prone to rapid oxide layer formation. Mild steel electrodes are cost-effective but susceptible to corrosion, requiring more frequent replacement. In contrast, stainless steel electrodes provide better corrosion resistance and relatively lower fouling compared to mild steel, making them more suitable for applications requiring long-term operational stability.

7.3 Mass Transfer Constraints

Poor contact between pollutants and electrode surfaces reduces treatment effectiveness; therefore, it is recommended to enhance mixing within the reactor by employing mechanical stirrers and optimizing flow velocity to improve pollutant–electrode interaction and overall process efficiency.

7.4 Inter-Electrode Spacing, Fluid Dynamics, and Byproduct Formation

Excessively small inter-electrode spacing can lead to the accumulation of hydrogen (H_2) bubbles and sludge between electrodes, thereby reducing the effective active surface area, causing localized overheating or minor bursts, and potentially promoting incomplete oxidation that results in harmful intermediate byproducts. Therefore, an optimal inter-electrode spacing of approximately 1–3 cm is recommended to facilitate smooth flow, efficient removal of gas bubbles and sludge, and adequate residence time, ensuring improved operational stability and complete pollutant removal (Al-Ajmi et al., 2025; Behera et al., 2026).

7.5 Thermal and Energy Management

Excessive heat generation during operation can compromise system stability and reduce the lifespan of system components; therefore, it is recommended to implement appropriate temperature control mechanisms and optimize operating conditions to ensure stable and efficient system performance.

8. Key Challenges

During the project, different practical and operational challenges were observed while working on the MDT based SMEP system for textile wastewater treatment.

- In the fabrication stage, the required materials were not easily available, so first their availability had to be confirmed. Based on that, the design was adjusted, which made the process slow and sometimes difficult to implement as originally planned.
- During transportation, reactor components were affected by vibrations, which disturbed alignment and loosened nuts and bolts.
- Loose terminal connections increase electrical resistance, which causes heating and unstable system performance.
- Setting the right current density helps remove pollutants properly while saving energy and protecting the electrodes.
- While setting up the reactor, electrode spacing (1–3 cm) was adjusted manually, but during operation and handling, slight movement occurred, which disturbed the alignment and affected performance.
- Electrodes can wear out and corrode over time, which reduces efficiency and increases maintenance.
- Fluctuations in wastewater characteristics require continuous adjustment of operating conditions to maintain consistent treatment performance.
- The formation of metallic hydroxide sludge requires efficient separation and management strategies.
- Long-term use can damage reactor materials, seals, and the overall structure.

- Throughout the project, regular monitoring was carried out, and adjustments were made whenever required to keep the system operating properly and to obtain consistent results.

9. Access to Finance

The successful scalability of the electrooxidation system in treating textile wastewater necessitates a fiscal strategy that corresponds to the level of development of the technology, risk level of textile mills, and financial dynamics of the mills. The use of industrial wastewater treatment technologies in Pakistan is mostly done according to their scientific validity. This can be realized through the implementation of a complete package that can help in removing compliance risks, alleviating water scarcity issues, enhancing the acceptance of exports to the market, and offering a practical means of cost recovery. The technical merits of electrooxidation are not, therefore, the only conditions to be met to gain finance, but also the way such prospective projects are packaged to build finance institutions (DFIs), export-oriented manufacturers, and engineering firms, and, in addition, public agencies. Wastewater treatment by only electrooxidation at the financing level cannot be viewed as an add-on environmental technology, but a strategic investment in industrial infrastructure. Therefore, an investment project would be much more appealing when it is perceived to have more than one benefit at a time. These involve the assistance of factories in meeting their environmental discharge requirements to mitigate reputational and buyer-related risks, increase water re-use, reduce dependence on freshwater supply, and protect the textile process against the effects of droughts and tightened regulations.

9.1 Financing requirement

The electrooxidation facilities are usually high-tier funded. A pilot trial, validation of how the system works, and reworking of the plan to adjust the reactor, based on the nature of the textile wastewater involved, all require the primary phase of financing. The second stage is the initial commercial capital of a plant-scale module, which can be operated in the conditions of a real facility. The third layer is the replication financing; the solution can be transferred at a few Mills or even an Industrial cluster. These electrooxidation systems include delicate parts of the power supply units, electrodes, hydraulic controls, and tools; points of interface with affluent treatment phases (e.g., equalization, pretreatment, biological treatment, and polishing), not to mention pumps, pipelines, or civil infrastructure. This means, just like banks and financial institutions, they eventually require more tangible evidence of reliable operation than what the current designs will offer, such as correct estimates of energy consumption per kilowatt-hour, average lifespan of electrodes, and service periods, before they are convinced to revert to the confidence they will need to deploy at a large scale.

9.2 Principal financing channels

Financing options for wastewater treatment and reuse projects in the textile sector vary depending on the scale of the project, the financial strength of the industry, and the level of technological advancement. In practice, a combination of internal funding, external financing, and collaborative investment approaches is often used to support implementation and long-term operation.

- Internal capital investment by textile industries allows faster implementation, especially for mills that already have environmental budgets or face strong export and compliance pressure.
- Commercial bank financing can support projects where companies have strong financial standing and the investment qualifies as plant modernization, compliance infrastructure, or water reuse systems.
- Lease or equipment financing is suitable for modular systems, where standardized units can be installed and maintained with support from local engineering partners.
- Development finance and concessional funding play an important role in pilot projects, technology demonstration, and initiatives related to cleaner production, water management, and industrial sustainability.
- Public-private co-financing is useful for shared treatment facilities, such as common effluent treatment plants, where multiple industries benefit from a centralized system.
- Supplier-backed or performance-based financing can be adopted when technology providers offer flexible payment options, performance guarantees, or build-own-operate arrangements.

9.3 Bankability requirements

The financing of the project must be bankable so that it can be made available on acceptable terms. A bankable electrooxidation project is not a scholarly work anymore, it is a formal investment memo that compiles process information and engineering foundation, economic assumptions, risk distribution, and implementation rationale. The lenders and investors will be interested in the positive response to five questions about what problem or problems you are solving, how repeatable a solution is in a real mill, what it will cost to construct and operate that, and, should performance not be as expected, what you will do. Therefore, a good financing dossier must comprise: a wastewater characterization profile; pilot / bench-scale testing on characterizing textile effluent; designed throughput; energy model; electrode replacement assumptions, operation philosophy, and spare components; implementation schedule, savings proforma with downside-case scenario. Sensitivity analysis should also be included in the proposal as far as possible to demonstrate how electricity tariffs, COD reduction lower than anticipated, reduced benefit on water reuse, and higher maintenance costs can be seen to affect the proposal.

9.4 Recommended financing structure by project stage

The financing approach for textile wastewater treatment projects typically evolves with the stage of project development, ranging from early pilot testing to full-scale implementation and cluster-level deployment. Each stage involves different types of funders, financial structures, and evidence requirements to ensure technical feasibility, financial viability, and operational reliability.

Table 6 Financing Structure and Requirements Across Different Project Stages.

Project stage	Typical funder	Preferred structure	Key evidence required
Bench/pilot demonstration	Grant, industry co-funding, innovation program	Shared-cost pilot or sponsored demonstration	Representative wastewater tests, pilot protocol, and monitoring plan
First commercial unit	Anchor mill, DFI-supported debt, concessional blending	Staged capex with milestone releases	Pilot results, EPC design basis, guaranteed minimum performance
Replication within one group	Commercial bank or internal capex	Standardized module finance	Operating history, actual opex, operator capability

Cluster or CETP deployment	Public-private partnership, blended finance	Shared infrastructure model	Governance model, user tariff, allocation of risk and responsibility

9.5 Financial packaging recommendations

A well-structured financial framework is essential to enhance the bankability and long-term sustainability of the project. This requires aligning the investment model with risk management, operational reliability, and measurable economic returns. The following recommendations outline key strategies to strengthen financial structuring and investor confidence:

- Reform the project as a compliance-and-reuse investment, not only as a treatment unit.
- Separate demonstration risk from scale-up risk. Pilot validation should not be financed with the same assumptions as a mature commercial plant.
- Use milestone-based disbursement tied to pilot completion, factory acceptance testing, and performance stabilization.
- Offer optional service contracts, so lenders know there is a designated team to operate and support the system, instead of leaving the owner alone with technology they may not fully understand.
- Where feasible, convert part of the value proposition into measurable recurring savings, especially by reusing water recovery, lowering discharge risk, and reducing external water procurement.

9.6 Key constraints in the Pakistan context

Pakistan textile industry is comprised of large-scale composite mills (mostly export-oriented) and medium scale units, which are characterized by unequal technological and financial potential. Little mills will be willing to construct more than the minimum required to meet the regulations, either, because they cannot see regulatory pressure, buyer pressure, or have a business case that makes any sense in terms of production continuity. As a result, willingness to finance throughout the sector varies significantly. The second concern is the cost and complexity that is perceived to surround maintaining advanced treatment technologies. This expectation is not completely unwarranted; electrooxidation may be economically non-optimal in cases where it is incorrectly applied to inadequately treated wastewater (e.g. untreated municipal wastewater), or when pooled electrical design, electrode choice and operational control are not well balanced. Therefore, financial structuring is to incentivize the intrinsic entrenching of the processes as opposed to reactor setups. Lastly, the foreign currency exposure also impacts on imported parts like specialized electrodes, rectifiers, sensors, control equipment, etc. The proper financing plan must specify what can be localized and what will have to be import-dependent as it directly reflects on the capex volatility/spare parts planning.

10. Recommendations to Industry

Framing electrooxidation in a way that connects with corporate decision makers will be critical to industry adoption. Mills do not typically invest in treatment technologies merely because they yield better removal efficiency on paper. They invest when the technology works within operational realities and can be supported by existing staff, as well as be integrated into a broader compliance and business strategy. Therefore, the following recommendations overview supports textile manufacturers, processing units, industrial estates, and sector associations to assess and implement electrooxidation responsibly. However, electrooxidation is more effectively utilized as a strategic advanced-treatment process, especially for color removal, COD reduction, toxicity attenuation, and polishing targeting reuse. And it certainly should not automatically be treated as a full substitution for all existing treatment infrastructure. In many cases, the most resilient and cost-effective route will involve hybridization with existing systems for equalization, coagulation-flocculation, sedimentation, biological treatment, filtration, and final polishing.

10.1 Adopt electrooxidation where it solves a clearly defined problem

Electrooxidation should be implemented in a targeted manner, focusing on applications where conventional treatment methods fail to meet performance requirements. Its adoption must be driven by specific operational gaps and clearly identified treatment challenges. The following conditions indicate where its application is most justified:

- Persistent non-compliance in color or COD despite operation of a conventional effluent treatment plant (ETP).
- Need for better consistency in effluent quality across changing dyeing recipes and production loads.
- Water reuse targets that cannot be achieved with biological treatment alone.

- Limited land availability for expanding conventional treatment units.
- Requirement for compact retrofits within an existing factory footprint.
- Need to improve environmental credibility for export-facing buyers and sustainability audits.

10.2 Avoid poor deployment practices

Without any previous assessment of the solids load, oil and grease, surfactants, shock loading, conductivity, pH range, and presence of compounds which might facilitate or inhibit electrochemical oxidation, raw wastewater cannot be put into technology. A poorly implemented deployment is normally an imposed electrooxidation not installed in the correct point inside the treatment train, but instead on all at the same time. Industry should not therefore succumb to the urge to buy a reactor as a single commodity without the characterization of wastewater, the analysis of pretreatment, hydraulic balancing and energy evaluation. It is not a question whether electrooxidation in principle will work; it is whether it will have to be installed in the plant and what performance it is likely to give.

10.3 Segment the market for deployment

Effective deployment of electrooxidation requires a clear understanding of market segments and their technical readiness. Different types of textile operations have varying treatment challenges and operational capacities. The following segmentation highlights the most suitable adoption pathways:

- Large composite mills with established ETPs: best candidates for advanced polishing and reuse enhancement.
- Denim and wet-processing units with difficult color profiles: suitable where conventional systems struggle with aesthetic and refractory loads.
- Industrial clusters and common treatment facilities: suitable for shared advanced treatment modules when multiple users face similar pollutant profiles.
- Medium-scale units with weak O&M capacity: should be adopted only through managed service or strong local support models, not through unsupported equipment purchase.

10.4 Recommendations for industry associations and cluster bodies

Industry associations and cluster organizations play a critical role in facilitating technology adoption and reducing implementation risks. Their involvement can help standardize practices, improve knowledge sharing, and build confidence among stakeholders. The following actions are recommended:

- Support shared demonstration programs so that multiple mills can observe performance on real textile wastewater.
- Prepare standardized technical specifications and evaluation criteria for advanced treatment packages.
- Engage with regulators and buyers to clarify realistic performance expectations and acceptable validation methods.
- Facilitate aggregated procurement of electrodes, instruments, and specialist maintenance support to reduce costs and supply uncertainty.
- Promote operator training and certification modules focused on advanced wastewater treatment.

10.5 Environmental and business messaging to industry

This needs to be tempered by the fact that it is a commercial message to an industry audience. Zero-maintenance operation and generality do not sell electrooxidation. Instead, it must be promoted as a rapidly scalable, modular, high-efficiency treatment technology with applications in new site-specific processes where conventional technologies have an endogenous complacency gap, or where quality water utilization is of strategic value. The industry should demonstrate that it is a viable and competitive business choice to invest in state-of-the-art wastewater treatment. Mills that will be able to sail a narrower ship around the treatment-related parameters, sustainable water practices, reasonable and traceable controls over their environmental footprint, will probably be in a better position since the store will be watched by the buyer.

11. Availability of Pilot Units for Demonstration and Related Considerations

The pilot scale demonstration is no more than that, the high-resolution path of proving the laboratory ambitions to make them commercially based. In the case of electrooxidation, these areas can be even more than marketing areas: these are the platforms to minimize risk. This is defined as location-specific information on energy demand, hydraulic performance, pollutant removal, behavior of the electrode stacks, fouling behavior, maintenance intervals, and interactivity of operators. Pilot validation: Since nearly all business projections are speculative, pilot transparency must be seen as a very important element in the level-up strategies. In the textile sector of Pakistan, the rollout of such systems could be done more pragmatically by treating actual wastewater streams over a long duration with one or more mobile pilot units.

11.1 Recommended pilot unit characteristics

A well-designed pilot unit is essential to validate performance under real industrial conditions and reduce scale-up risks. It should be flexible, robust, and easy to operate while capturing all necessary operational data. The following characteristics are recommended:

- Containerized or skid-mounted format for transport between industrial sites.
- Flexible throughput, ideally in the range of approximately 5 to 20 m3/day for demonstration purposes.
- Ability to operate in batch and continuous modes to test different hydraulic strategies.
- Integrated instrumentation for pH, conductivity, flow, voltage, current, specific energy consumption, and basic alarms.
- Provision for upstream filtration or cartridge protection where the solids load is variable.
- Simple but reliable control logic so local operators can run supervised demonstrations without excessive complexity.

11.2 Why pilot units matter commercially

A pilot unit responds to questions that are critical for the approval of investment. It indicates if the intended effluent stream is amenable to electrooxidation, what removal efficiency will be achieved in the long term, whether a conductivity adjustment is needed or not, how sensitive performance is with respect to pH, and how much work an operator will have to do. It also indicates if the technology should be applied to biologically treated effluent, segregated high-strength streams, mixed wastewater, or reuse-loop polishing. The pilot builds confidence among financiers, factory managers, and regulators alike, from a commercial perspective. It changes the discussion from vague technology assertions to site-specific operational proof. In

Pakistan, the buyers and mill owners are generally hesitant when it comes to adopting up-to-date systems without a tangible return on investment in know-how

11.3 Suggested pilot deployment protocol

A well-defined pilot deployment protocol ensures the systematic validation of system performance under real industrial conditions. It provides a clear framework for testing, optimization, and data collection essential for scale-up decisions. The recommended deployment stages are presented below:

Table 7 Suggested protocol for pilot deployment and performance validation.

Stage	Indicative Duration	Primary Objectives	Expected Deliverables
Site assessment	1-2 weeks	Confirm wastewater source, integration point, utilities, and sampling plan	Trial workplan and operating envelope
Commissioning and shakedown	1 week	Stabilize hydraulics, safety, controls, and pretreatment interfaces	Baseline operating settings
Performance run	6-10 weeks	Assess treatment efficiency, energy demand, and operational reliability under varying wastewater conditions	Verified performance dataset
Optimization run	2-4 weeks	Refine pH, retention, current density, and integration logic	Design and operating recommendations for scale-up

11.4 Demonstration metrics that must be measured

Accurate and comprehensive performance evaluation is critical during pilot and demonstration phases. Key technical, operational, and economic indicators must be consistently monitored to ensure reliable assessment. The following metrics should be measured:

- Influent and effluent COD, color, TSS, conductivity, pH, and, where relevant, TOC, BOD, and toxicity indicators.
- Specific energy consumption per cubic meter treated and, where appropriate, per kilogram COD removed.
- Electrode condition and cleaning/replacement intervals.
- System uptime, downtime causes, and maintenance events.
- Operator-hours required per shift or per cubic meter treated.
- Compatibility with downstream reuse, polishing, or discharge objectives.

11.5 Related considerations for pilot planning

Pilot campaigns must be conducted to ensure representative process variability. The composition of textile wastewater varies according to product mix, dye chemistry, washing conditions, and production intensity. A brief and highly selective demonstration may yield unrealistically positive outcomes. Therefore, for the experiment to be conclusive, the pilot should cover both standard operating periods and more challenging periods. When determining which technology or technique should be shown as the best demonstration choice, observers should also think about how things could evolve in the future.

This includes stable power availability, safe drainage, handling of samples, pilot skid accessibility, and determinations for who will be responsible for routine operation and emergency shutdown. A pilot can fail commercially if it gets stuck in a factory environment without sufficient operational ownership; perhaps the chemistry was not unsound at all. Ultimately, pilot data will also need to be packaged into a formal scale-up package. What they should be producing is not graphs and laboratory reports. It shall cover an undocumented design basis memorandum, budgeted CapEx and OpEx range, recommended process configuration, risk log, operation and maintenance requirements, and should have a clear statement of the conditions under which the results were obtained.

12. Opportunities and Pathways for Scaling the Solution Further

The long-term value of electrooxidation treatment is not limited to proving that pollutants can be removed at one location, but rather it is in creating replicable pathways for wider market adoption. Hence, scaling needs to be understood in multi-dimensional levels: scale of single plant, scale across several mills within a textile group, scale through local engineering standardization & scaling up for cluster level/common treatment. In a staged scaling model, the economics and operating complexity of the technology can improve dramatically if operational lessons from early deployments feed back into proposed standard designs, service/package arrangements, operator training programs, and local/component sourcing.

12.1 Pathway A: retrofit polishing within existing mills

This is the easiest first scaling trail. Several of the larger textile mills currently have equalization tanks, primary clarification, biological treatment, and some type of tertiary polishing in place. Yet, they remain challenged with color, refractory organics, variability, and reuse-quality requirements. In such scenarios, electrooxidation can be employed as a modular post-treatment polishing stage. The good thing about this pathway is that the bulk of the hydraulic and civil infrastructure is already built. The electrooxidation package can thus be sized closer to the residual treatment gap, improving both economics and time to deployment.

12.2 Pathway B: targeted treatment of segregated high-strength streams

In some factories, a better commercial strategy may be to segregate specific wastewater streams that carry the highest color or refractory load rather than sending the full mixed effluent flow to electrooxidation. This pathway is especially useful if a department or process step generates an inordinate hard-to-treat fraction of the wastewater. It is highly cost-effective to treat separated streams because the advanced oxidation duty is only used where it adds maximum value. It also enables improved process control and can shrink the reactor volume needed.

12.3 Pathway C: reuse-enabling integration

These reasons are gradually making water shortage a strategic business issue for the Pakistani industry. Scaling of electrooxidation will be supported by the business case of the reuse of water instead of discharge compliance. Here, the system belongs to a robust recycling cycle with other treatment mechanisms such as filtration, adsorption, membrane treatment, or even final disinfection based on the final use need. This path is particularly attractive in places where mills are either experiencing increasing costs or where there is doubt as to the availability of freshwater. Reprocessing will also help with environmental performance and operating resilience through this technology.

12.4 Pathway D: cluster-level and common effluent treatment plant (CETP) applications

Factory clusters with similar challenges, including e.g. industrial estates or textile clusters where many units generate the same form of waste and compliance requirements, but do not have the financial capacity for a fully independent advanced treatment plant in each unit, may also become practicable through a shared-treatment model. Several models can impose the electrooxidation as a final polishing unit with a common centralized treatment facility or a different modularized add-on with common challenging streams. This may be particularly relevant in regions where environmental regulation is getting stricter, or the public authorities may desire to promote more environmentally clean industrial areas. It is a road that needs better governance, incentives/tariffs restructuring, and institutional coordination, but also encapsulates more sectoral impetus.

12.5 Pathway E: localization and manufacturing scale-up

Localization and scale-up are essential to reduce costs, improve supply chain reliability, and ensure long-term sustainability of the technology. A structured approach is required to balance local manufacturing with strategic imports. The following steps outline this pathway:

- Standardize skid designs, piping type, panel, and instrumentation packages.
- Localize frame, tank, interconnecting pipework, housing, and electrical enclosures fabrications.
- Develop an accepted supplier list of consumables, sensors, cables, valves, and maintenance items.
- Only maintain import channels for strategic imports of special components that are economically infeasible to localize currently.
- Train domestic EPC and O&M staff to guarantee that the solution is not based on constant foreign technical assistance.

12.6 Preconditions for sustainable scale-up

Further scaling cannot be achieved only by enthusiasm. It will be supported with performance data in at least some of the representative textile wastewater conditions, documented O&M procedures, an operator training package, and a local support model of spare parts and troubleshooting. Moreover, the deeper the solution is integrated into the procurement standards, engineering specifications, and sustainability roadmaps before buyers, the more sustainable the scale-up will be. The reality is that once technology becomes a commonly accepted institutional practice and is no longer a single demonstration, market adoption may become speedy.

13. Overview of costs associated with scaling the solution to full commercial scale in the pakistan context

The pivotal point of any decision about full commercial scale-up is a realistic cost overview. In the case of electrooxidation, cost analysis should be managed with caution since performance and operating cost are extremely sensitive to wastewater content, pretreatment, conductivity, target removal of a particular pollutant, power tariff, electrode choice, hydraulic residence time, and the degree of automation required. No universal cost for all textile facilities exists. Based on that, the cost framework below must be perceived as a rough-cut planning model of Pakistan, but not as an alternative to a comprehensive EPC estimate. This is intended to find out the primary cost drivers, create reasonable budgeting areas, and explain how the return on investment can be measured.

13.1 Main CapEx components

Understanding capital expenditure components is crucial for accurate project budgeting and financial planning. These costs include core process equipment as well as supporting infrastructure and engineering requirements. The main components are as follows:

- Electrooxidation reactor modules and electrode assemblies.
- Rectifiers, power supply units, Motor Control Centers, cabling, and electrical protection systems.
- Feed pumps, recirculation pumps, valves, manifolds, and interconnecting pipework.
- Instrumentation including flowmeters, conductivity meters, pH sensors, current and energy measurement, and control panel interfaces.
- Skid fabrication, mounting frames, tanks, filtration protection, and minor civil works.
- Automation, Supervisory Control and Data Acquisition, integration where required, and safety interlocks.
- Engineering design, site installation, commissioning, trial operation, and performance testing.

13.2 Main OpEx components

Operational expenditure plays a key role in determining the long-term economic feasibility of the system. Managing recurring costs effectively is essential for sustainable operation. The primary OpEx components include:

- Electricity consumption, which is often the largest controllable operating cost.
- Electrode wear, cleaning, maintenance, and scheduled replacement.
- Supporting chemicals were needed for pH correction, pretreatment support, or cleaning.
- Operator labour, supervision, and laboratory testing.
- Routine maintenance of pumps, sensors, panels, and auxiliary equipment.
- Residual management, including handling of any upstream pretreatment sludge or spent cleaning media.

13.3 Indicative CaEex ranges for Pakistan planning

Estimating capital expenditure across different plant scales is critical for financial planning and investment decision-making. Costs vary depending on system capacity, level of automation, and degree of localization. The indicative CapEx ranges for Pakistan are summarized below.

Table 8 Indicative capital expenditure ranges for electrooxidation systems across different plant scales in Pakistan.

Plant scale	Indicative throughput	Indicative capex range	Comment
Pilot / pre-commercial	5–20 m^3/day	PKR 40 to 100 million	Depends on mobility, instrumentation, and imported content
Small commercial module	100–300 m^3/day	PKR 110 to 280 million	Suitable for polishing or segregated-stream treatment

Medium commercial plant	500 m^3/day	PKR 220 to 500 million	Usually requires stronger integration and automation
Large commercial plant	1,000 m^3/day or more	PKR 420 to 980 million	Best justified where reuse or major compliance value is captured

13.4 Indicative OpEx range

A wise initial operating-cost envelope of the electrooxidation stage with respect to planning in Pakistan could be assumed to lie in the wide range of about PKR 80 to PKR 350 per cubic meter of treated material in the range of process duty. The lower end is more realistic, where the system is treating a well-treated stream with good conductivity and a moderate polishing goal. It is more likely in the upper end, where the stream is stronger, the oxidation target is high, or energy and maintenance optimization are weak. This range cannot be taken as a sales promise. Rather, it ought to be an early budgeting instrument until pilot data and engineering design can refine the estimate based on the specifics of the site.

13.5 ROI logic and value drivers

One should not ever look at the value of electrooxidation in terms of its direct comparison with the costs of conventional technologies. In several industrial scenarios, what promotes the actual economic worth is noncompliance, less buyer risk, water reuse terms, less susceptibility to droughts, and greater long-term operability of the treatment train.

The most common key value drivers are minimization of freshwater purchase or abstraction, reduced risks of production disruption as a result of environmental issues, increased effluent regularity, reduced costs of remedial actions when standard treatment facilities fail, and reputational benefits in export markets. In the case where these advantages are actual and quantifiable, it may cause the commercial case to become so strong as to overcome even the actual cost of undertaking advanced treatment of electricity.

13.6 Illustrative payback interpretation

The financial viability of electrooxidation systems depends strongly on the specific industrial context and operational conditions. Payback periods can vary significantly based on compliance pressure, reuse potential, and system management. The following scenarios provide an indicative interpretation:

- Large export-oriented mill, clear compliance pressure, significant reuse value, and good upstream pretreatment. Indicative payback may be in the range of roughly 2.5 to 5 years.
- Mill needs polishing but has weaker reuse value or uncertain operating discipline. Payback may extend to 4 to 7 years.
- Plant attempts to use electrooxidation as a substitute for poor basic treatment or lacks internal ownership. Payback may be unattractive unless the configuration is redesigned.

13.7 Cost reduction strategy for commercial scale-up

Achieving cost competitiveness at commercial scale requires a combination of technical optimization and strategic planning. Reducing both capital and operational expenses is essential for wider adoption. The following strategies can support cost reduction:

- Use electrooxidation on the right stream and at the right stage of the treatment strategy.
- Maximize equalization and pretreatment to reduce unnecessary advanced-treatment burden.
- Standardize reactor and panel designs across sites to reduce engineering duplication.
- Localize fabrication of non-specialized components.
- Include remote monitoring and preventive maintenance so unplanned failures do not raise lifecycle cost.
- Negotiate long-term supply arrangements for electrodes and critical spares.

14. Commercial Roll-Out Plan in Collaboration with Local Engineering Partners and Key Industry Stakeholders

The commercial roll-out of emerging technologies should be envisioned more as a structured market-entry and capability-building program than just an equipment sale. This is essential in the new technology, such as electrooxidation, where initial installations predetermine the market. Finally, a disciplined roll-out model can help in mitigating technical risk, enhance local ownership, and enhance investor confidence, which will establish the base of widespread replication in the Pakistani textile industry. According to the evaluation above, the business strategy used is the establishment of a local ecosystem for the solution. This ecosystem is to include the technology developer or knowledge partner; a qualified local engineering/EPC firm, one or more local textile mills in the area; laboratory and monitoring services/support; an operator training facility, and funding arrangements. These roles being known at the start, market adoption will be quicker and more sustainable.

14.1 Proposed roll-out phases

A well-defined pilot deployment protocol ensures systematic validation of system performance under real industrial conditions. It provides a clear framework for testing, optimization, and data collection essential for scale-up decisions. The recommended deployment stages are presented below.

Table 9 Suggested protocol for pilot deployment and performance validation.

Phase	Focus	Lead actors	Indicative duration	Key deliverable
Phase 1	Pilot validation	Technology team, host mill, lab partner	3-4 months	Site-validated performance dossier
Phase 2	Anchor commercial installation	Host mill, EPC partner, financier	4-8 months	First bankable commercial unit
Phase 3	Standardization and localization	EPC partner, fabricators, suppliers	6-12 months	Replicable module design and support model
Phase 4	Sector expansion	Industry associations, multiple mills, and financiers	Ongoing	Portfolio of deployments and market adoption

14.2 Role of local engineering partners

Local engineering partners are also the key to commercial success. They simplify the technology to ensure that the Pakistani industry can purchase, install, use, and maintain it. Site surveys, piping and instrumentation design, skid fabrication, electrical works installation and integration into existing treatment infrastructure, along with the commissioning support, may fall under their expertise as well as after-sales maintenance. Even troubleshooting, retraining operators, minor redesign, stocking spare parts, and performance follow-up should also be undertaken by a good local partner. This kind of local presence can increase self-sufficiency in the imported technical support and convince lenders that the plant can be brought into service over time.

14.3 Key industry stakeholders and their expected roles

Successful deployment of advanced treatment technologies depends on coordinated efforts among multiple stakeholders. Each group plays a distinct role in supporting adoption, validation, and long-term operation. The following outlines their expected contributions:

- Anchor textile mills: host pilots, supply wastewater data, co-invest in the first commercial deployment, and provide operational feedback.
- Industry associations: help identify candidate mills, disseminate results, support standard setting, and improve sector trust.
- Provincial environmental regulators: clarify compliance expectations and encourage verified demonstration under approved protocols.
- Financiers and DFIs: support pilot-to-commercial transition through debt, blended finance, or concessional support.
- Universities and research laboratories: assist in verification testing, process optimization, and independent technical review.
- Technology suppliers and OEM partners: define electrode strategy, power-supply specifications, operating envelope, and design updates.

14.4 Implementation safeguards

To ensure reliable performance and minimize operational risks, strong implementation safeguards must be incorporated from the outset. These measures help maintain system stability, accountability, and long-term success. The following safeguards are recommended:

- Use defined acceptance criteria for treatment performance, energy use, and stability before final handover.
- Include operator training, SOP manuals, preventive maintenance plans, and emergency-response procedures in the commercial package.
- Maintain spare-part availability for critical equipment and identify local response times.
- Embed remote monitoring and periodic performance review in the first installations.
- Use contract structures that clearly allocate responsibility for wastewater variability, utilities availability, and upstream pretreatment quality.

14.5 Suggested roadmap for the first 24 months

In the first half of the year, the textile mills candidate will be determined, wastewater screening will be conducted, pilot units will be deployed, and evaluation protocol created. Extensive engineering of the two best demonstration sites will begin between 6 and 12 months. One of the elements of business performance is delivered over a wider scope, 12-18 months. The first production system goes online and is stabilized and formal performance reported. Between 18 to 24 months, the solution should evolve into a standardization, capacity building and active business development process to other replica locations.

14.6 Concluding implementation note

A partnerships-based model with known demonstrations backed by home-grown engineering strength, disciplined cost management, and prudent positioning of the technology is, however, the only realistic entry route to the market in Pakistan. Although electrooxidation may be an appealing clean-up technology to use in the treatment of industrial-scale textile wastes, the fact is that effective commercial implementation would demand a complete system-development orientation, as opposed to mere equipment-order placement. This latter combination of final project submission, or donor-facing report, will also annex sample technical specifications, pilot TORs, draft EPC scopes, and O&M outlines for immediate next-step action, as well as a financial model template.

15. Comparison of Factory Performance with Laboratory Targets

The factory-scale test confirmed the treatment system-maintained efficacy under actual operating conditions of the factory industry and offered considerable elimination of key wastewater quality parameters. Significant changes were observed in total suspended solids

(TSS), total dissolved solids (TDS), turbidity, chemical oxygen demand (COD), biochemical oxygen demand (BOD), and heavy metals on all tested configurations, which confirmed the ability of the process to maintain stable treatment performance throughout the entire operation. Among the tested materials, in general, aluminum was the most effective in overall performance, followed by mild steel, and in most cases, stainless steel had a lower removal efficiency. These results provide strong indications that the technology is practical at the factory level, and not at laboratory-level conditions only.

The highest treatment effects in terms of the greatest removal of suspended matter, biodegradable organic load, and metallic contaminants were found in turbidity, TSS, BOD, and heavy metals. Reduction in COD also showed that useful oxidation of the wastewater's organic load was also achieved, although at a level of production performance below that of the laboratories that had an ambition of up to 98% removal of all meaningful pollutants. The removal of TDS was moderate compared to the others, proving the fact that dissolved salts and ionic species may be more difficult to eliminate than particulate and biodegradable components. This is particularly so when it comes to the treatment of textile wastewater, dissolved solids, and remaining salinity are major factors that control the quality of the effluent, but internal recycling is also a factor.

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Still, the current results do offer indirect evidence of technology’s commercial potential down the line. The consistent performance trends observed, along with the high reduction rates achieved in both suspended and organic pollutants, and the excellent behavior of aluminum as electrode material, constitute a solid foundation on which to base further optimizations or scaling-up of the system. In particular, the measured removal of TSS, turbidity, BOD, COD and heavy metals is a sign that the quality of treated water approaches a point where it can be used again but due to significantly smaller reduction in TDS compared to other contaminants implies that additional polishing or combination with other treatment technologies must be considered before high levels of reuse could be asserted with confidence. As such, the factory trials show that the system is an attractive candidate for industrial implementation, but further rounds of techno-economic, energy, emissions, and reuse validation will be necessary to corroborate the full suite of laboratory-derived statements at a large commercial scale.

15.1 Key Technical Observations from Factory-Scale Trials

Factory-scale trials provide critical insight into the real-world performance of the electrooxidation system under variable industrial conditions. These observations reflect the system's ability to handle complex wastewater characteristics and validate its technical effectiveness beyond controlled laboratory environments. The key findings are summarized below.

Table 10 Summary of key technical performance observations from factory-scale electrooxidation trials.

Parameter	General Observation	Interpretation
TSS	Strong reduction	Good removal of suspended matter
TDS	Moderate reduction	Dissolved salt remained comparatively difficult to remove
Turbidity	Very strong reduction	Significant improvement in visual and particulate quality
COD	Significant reduction	Effective oxidation of organic pollutants, but below the laboratory target
BOD	Strong reduction	Good removal of biodegradable organic matter
Heavy metals	Good to very strong reduction	Effective reduction of metallic contaminants

Best-performing material	Aluminum	Most suitable electrode for further scale-up

15.2 Summary of Factory-Scale Performance Relative to Laboratory Targets

A comparison between laboratory targets and factory-scale results is essential to evaluate the scalability and practical feasibility of the technology. While some variation is expected due to fluctuating wastewater quality, the pilot results demonstrate strong alignment with initial performance expectations. The comparative assessment is presented below.

Table 11 Comparative assessment between laboratory targets and factory-scale performance of the electrooxidation system.

Targets	Pilot Plant Results	Observation
Removal efficiency of up to 98% of all significant pollutants	Significantly achieved	- An 89-93% removal efficiency was achieved for industrial raw wastewater. - In terms of parameters, COD, BOD, and TSS showed approximately more than 90% reduction. - The fluctuation of removal efficiency was dependent on the variation in the quality of wastewater coming from the plant.
Lower capital outlay (40% less than conventional systems)	Achieved	- A 41% reduced cost was achieved for the pilot scale plant in comparison with the voluminous running plant. - Industrial technology can provide treatment at 380-600 PKR/m^3 for the entire process. In comparison, our treatment at pilot scale gives 270-300 PKR/m^3.
Lower energy costs (50-60%) and associated emissions savings	Significantly achieved	- A 55% reduced energy consumption was achieved. - Industrial technology can provide treatment at 3.9-4.5 kWh/m^3 for the entire process. In comparison, our

		treatment at pilot scale gives 2.4-2.8 kWh/m^3.
Water reuse ability of up to 90%	Achieved	- Treated water was recovered in 85-92% ranges, while the remaining content was only sludge. The water quality was suitable for irrigation usage.

16. List of Publications

16.1 Journal Publications

Title: Performance evaluation of novel cascade aerating trickling filter: contaminants removal and biodegradation model
Authors: R. M. A. Kanwar, Z. M. Khan, M. Shoaib, H. U. Farid, M. Sultan, A. Shakoor, F. Ahmad, A. Ullah, M. W. Shahzad, S. F. Javaid, A. Ameen
Journal: International Journal of Environmental Science and Technology
DOI: 10.1007/s13762-025-06438-w

Title: A machine learning approach to wastewater treatment: Gaussian process regression and Monte Carlo analysis
Authors: Nimra Nadeem, Zubair Khaliq, Abdulaziz Bentalib, Muhammad Bilal Qadir, Fayyaz Ahmad, Muhammad Wakil Shahzad, Abdulrahman Bin Jumah
Journal: Nanoscale Advances
DOI: 10.1039/D4NA01064G

Title: AI-powered optimization of reactive red 195 dye decolorization: Evaluating the impact of operational factors
Authors: Zubair Khaliq, Anum Javaid, Abdulaziz Bentalib, Muhammad Bilal Qadir, Zubera Naseem, Shumaila Kiran, Fayyaz Ahmad, Nimra Nadeem, Maryam Bibi
Journal: Desalination
DOI: 10.1016/j.desal.2025.118936

Title: Fabrication of zinc oxide/sodium alginate nanocomposite for effective catalytic degradation of Direct Yellow 44 dye: A sustainable approach
Authors: Shumaila Kiran, Abdulaziz Bentalib, Alina Javaid, Mubashar Hussain, Muhammad Wakil Shahzad, Zubair Khaliq, Muhammad Bilal Qadir, Zaryab Rashid
Journal: Desalination and Water Treatment
DOI: 10.1016/j.dwt.2025.101028

Title: Advanced Hybrid Nanotechnology Driven Pathways for Biofuel Generation from Biomass and Wastewater: A Comprehensive Review
Authors: Zubair Khaliq, Kashif Ali, Nimra Nadeem, Muhammad Bilal Qadir, Muhammad Zahid, Zubera Naseem, Muhammad Wakil Shahzad, Tanveer Hussain
Journal: Waste and Biomass Valorization
DOI: 10.1007/s12649-026-03506-1

Title: Recent Advancements in WO_3-based polymeric nanocomposites for photocatalytic applications: A Comprehensive Review
Authors: Hira Abbas, Zubair Khaliq, Nimra Nadeem, Muhammad Bilal Qadir*, Muhammad Ubaid-Ur-Rehman, Danish Umer, Zubair Jilani, Muhammad Wakil Shahzad*
Journal: Journal of Chemical Sciences (Accepted Article)
DOI: 10.1007/s11696-026-04708-6

Title: A critical review on advance molecular distortion techniques for textile wastewater treatment in Pakistan
Authors: S Ashraf, M Sultan, MW Shahzad, M Imran, RMA Kanwar, MN Ashraf, ZM Khan, Z Khaliq, MB Qadir
Journal: Water, Air, & Soil Pollution
DOI: 10.1007/s11270-026-09339-x

Title: Comprehensive review of desalination: Techniques, renewable energy integration, and the role of artificial intelligence
Authors: Saud Jamil, Muhammad Ahmad Jamil, Jawad Mustafa, Muhammad Wakil Shahzad
Journal: International Communications in Heat and Mass Transfer
DOI: 10.1016/j.icheatmasstransfer.2025.110733

Title: Synthesis and characterization of mesoporous caged silica for efficient adsorption of methylene blue from aqueous solution
Authors: Sundus Khushnood, Javaid Rabbani Khan, Sajjad Hussain, Hammad Khan, Fazal Wahab, Kim Choon Ng, Muhammad Wakil Shahzad
Journal: International Communications in Heat and Mass Transfer
DOI: 10.1016/j.icheatmasstransfer.2024.107706

Title: Machine learning-based process design of a novel sustainable cooling system
Authors: Muhammad Ahmad Jamil, Waqar Muhammad Ashraf, Nida Imtiaz, Ben Bin Xu, Syed M. Zubair, Haseeb Yaqoob, Muhammad Imran, Muhammad Wakil Shahzad
Journal: Energy Conversion and Management
DOI: 10.1016/j.enconman.2024.118941

Title: Hydro-thermal performance of an I-shaped pin fin microchannel heat sink with variable pin fin height, thickness and orientation
Authors: Hussain Sallar, Muhammad Irfan, Muhammad Mahabat Khan, Muhammad Wakil Shahzad
Journal: International Communications in Heat and Mass Transfer
DOI: 10.1016/j.icheatmasstransfer.2025.108256

Title: Recent advances in applications of MXenes for desalination, water purification and as an antibacterial: a review
Authors: Hicham Meskher, Amrit Kumar Thakur, Soumya Kanti Hazra, Md. Shamim Ahamed, Ahmed Mortuza Saleque, Qusay F. Alsalhy, Muhammad Wakil Shahzad, Md. Nahian Al Subri Ivan, Shuvra Saha, Iseult Lynch
Journal: Environmental Science: Nano
DOI: 10.1039/D4EN00547C

16.2 Conference Paper, Talks and Presentations

Title: Advanced molecular distortion for textile wastewater circularity
Authors: Muhammad Wakil Shahzad, Sahrish Ashraf, Hafiz Muhammad Umar Raza. Muhammad Sultan
2026 IDRA World Congress, 1-5 November, Riyadh, Kingdom of Saudi Arabia

Title: Molecular Distortion-based Advanced Wastewater Treatment for Pakistan's Textile Industry
Authors: Dr. Muhammad Sultan, Associate Professor, Bahauddin Zakariya University, Multan
3rd International Conference on Precision and Sustainable Agriculture under Climate Change, held on 12–13 February 2026, at KFUEIT, Rahim Yar Khan.

Title: Towards Molecular Distortion-based Wastewater Treatment in Pakistan's Textile Industry
Authors: Dr. Muhammad Sultan, Associate Professor, Bahauddin Zakariya University, Multan
SAFECONOMY Workshop: "Re-inventing the Textile Circular Economy"
Water and Energy Expo 2025, held at the Expo Center Lahore on 22-24 September 2025.

Title: Status and Challenges of Textile Wastewater Treatment in Pakistan
Authors: Dr. Muhammad Sultan, Associate Professor, Bahauddin Zakariya University, Multan
SAFECONOMY Workshop: "Re-Inventing the Textile Circular Economy", held at the Pakistan Water & Energy Exhibition & Conference at Karachi on Dec 3rd 2024.

Title: Advancing Textile Wastewater Treatment in Pakistan: Insights and Innovations with the Molecular Distortion Technique
Authors: Dr. Muhammad Sultan, Associate Professor, Bahauddin Zakariya University, Multan
4th International Conference on Polymers and Composites (ICPC-2024), organized by the National Textile University, Faisalabad-Pakistan on 26-27 November 2024.

Title: Leveraging Al and data science for enhanced wastewater treatment processes.
Authors: Dr. M. Bilal Qadir and Dr. Zubair Khaliq, Associate Professor, National Textile University, Faisalabad
SAFECONOMY Workshop: "Re-Inventing the Textile Circular Economy", held at the Pakistan Water & Energy Exhibition & Conference at Karachi on Dec 3rd 2024.

Title: Carbon Footprint & Water Stewardship
Authors: Dr. M. Bilal Qadir, National Textile University, Faisalabad, Pakistan
Eco-Textile Conference 2.0 (Lahore Edition 2025)

Title: Sustainable Materials in Circular Textile Economy: Bridging Innovation with Industrial Scalability
Authors: Dr. M. Bilal Qadir, National Textile University, Faisalabad, Pakistan
SAFECONOMY Workshop: "Re-inventing the Textile Circular Economy"

Water and Energy Expo 2025, held at the Expo Center Lahore on 22-24 September 2025.

Title: Nanotechnology for wastewater purification
Authors: Dr. Zubair Khaliq, National Textile University, Faisalabad, Pakistan
SAFECONOMY Workshop: "Re-inventing the Textile Circular Economy"
Water and Energy Expo 2025, held at the Expo Center Lahore on 22-24 September 2025.

16.3 Thesis

M.Eng. Thesis

Thesis Title: Study on Advanced Oxidation Techniques for Textile Wastewater Treatment
Candidate: Ms. Fatima Akhtar
Supervisor: Dr. Muhammad Sultan, Co-Supervisor: Dr. Muhammad Wakil Shahzad
Degree: M.Sc. (Hons.) Agricultural Engineering
Degree Awarding Institute: Bahauddin Zakariya University, Multan, Pakistan

PhD Thesis

Thesis Title: Multifunctional Optimized Caged Silica; Enhancing Desalination and Dye Removal Efficiency
Candidate: Sundus Khushnood
Degree: Doctor of Philosophy (PhD) in Chemical Engineering
Degree Awarding Institute: Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Pakistan

Thesis Title: Study on Advanced Molecular Distortion Technique-based Textile Wastewater Treatment System for Pakistan
Candidate: Sahrish Ashraf
Supervisor: Dr. Muhammad Sultan, Co-Supervisor: Dr. Muhammad Wakil Shahzad
Degree: Doctor of Philosophy (PhD) in Agricultural Engineering **(3rd Year–Thesis in Progress)**
Degree Awarding Institute: Bahauddin Zakariya University, Multan, Pakistan

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