

Integrated Coagulation-Adsorption-Filtration-Ceramic Membrane System for the Treatment of Songket Dyeing Wastewater

Rizki Rinaldi¹, Muhammad Said^{1,2*}, Desnelli^{1,2}

¹ Master's Program in Chemistry, Faculty of Mathematics and Natural Science, Sriwijaya University, Jln. Raya Palembang Prabumulih KM 32 Indralaya Ogan Ilir, Indonesia, 30662

² Departement of Chemistry, Faculty of Mathematics and Natural Science, Sriwijaya University, Jln. Raya Palembang Prabumulih KM 32 Indralaya Ogan Ilir, Indonesia, 30662

*Corresponding Author: saidusman2011@gmail.com

Abstract

This study investigated an integrated treatment system combining coagulation, adsorption, filtration, and ceramic membrane processes for songket dyeing wastewater. Textile wastewater is characterized by high color intensity, suspended solids, and organic loads, which can cause serious environmental impacts if discharged without adequate treatment. Coagulation using aluminum sulfate effectively destabilizes colloidal particles, followed by adsorption with activated carbon to remove dissolved dyes and organic compounds. Multimedia filtration and ceramic membrane filtration further enhance pollutant removal through physical separation mechanisms. The integrated system successfully achieved color reduction from 976.5 Pt-Co to 10.6 Pt-Co, TSS reduction exceeding 98%, and COD reduction above 93%, in accordance with Indonesian wastewater discharge standards for the textile industry (KLHK, 2016).

Keywords: Songket Wastewater, Coagulation, Adsorption, Filtration, Ceramic Membrane

Article Info

Received 23 January 2026

Received in revised 2

February 2026

Accepted 3 February 2026

Available Online 28

February 2026

Abstrak (Indonesian)

Penelitian ini menganalisis sistem pengolahan terpadu yang menggabungkan proses koagulasi, adsorpsi, filtrasi, dan membran keramik untuk air limbah pewarnaan songket. Air limbah tekstil dicirikan oleh intensitas warna yang tinggi, padatan tersuspensi, dan muatan organik, yang dapat menyebabkan dampak lingkungan yang serius jika dibuang tanpa pengolahan yang memadai. Koagulasi menggunakan aluminium sulfat efektif mengganggu kestabilan partikel koloid, diikuti dengan adsorpsi dengan karbon aktif untuk menghilangkan pewarna terlarut dan senyawa organik. Filtrasi multimedia dan filtrasi membran keramik semakin meningkatkan penghilangan polutan melalui mekanisme pemisahan fisik. Sistem terintegrasi ini mencapai pengurangan warna dari 976,5 Pt-Co menjadi 10,6 Pt-Co, penghilangan TSS melebihi 98%, dan pengurangan COD di atas 93%, sesuai dengan standar pembuangan air limbah Indonesia untuk industri tekstil (KLHK, 2016).

Kata Kunci: Air Limbah Songket, Koagulasi, Adsorpsi, Filtrasi, Membran Keramik

INTRODUCTION

The songket weaving industry in South Sumatra, Indonesia, is renowned for producing luxurious fabrics with detailed gold and silver motifs. However, the dyeing process uses synthetic dyes such as reactive, direct, and acid dyes, producing large volumes of colored wastewater rich in organic pollutants, suspended solids, and heavy metals (Cr,

Cu, Pb) [1]. Typical characteristics of this wastewater include high color intensity (500–3000 Pt-Co), Chemical Oxygen Demand (COD) of 800–2500 mg/L, Total Suspended Solids (TSS) of 200–600 mg/L, and alkaline pH (9–11) [2,3]. Untreated discharge can have a detrimental impact on aquatic ecosystems, reducing light penetration, oxygen levels and causing bioaccumulation of heavy metals [4].

Common textile wastewater treatments include coagulation-flocculation to remove suspended solids [5], adsorption using activated carbon to remove dyes and organic pollutants, filtration for solids separation, and membrane processes for dissolved contaminants [6,7]. Ceramic membranes are particularly promising due to their chemical resistance, durability, and high flux. Integrating these processes can improve treatment efficiency and cost-effectiveness [8].

Ceramic membranes were the efficient materials for wastewater treatment method. Studies from Kouzi et al. [9] said that advanced low-cost ceramic composite using rGO-TiO₂-pPD on kaolinite support have more than 93% rejection for various dyes with high water permeance. Combination from other local materials like clay, almond shell, lime which sintered at 900-1000°C for eco-friendly ceramic were significant useful for dye removal with 78-92% with good permeability & fouling resistance [10,11]. The nanofiltration from membrane was most effective for dye removal which can be integrated to treatment songket wastewater especially for local wastewater in Palembang city.

Despite its important cultural and economic value, sustainable wastewater management for the songket industry remains under-researched. Membrane filtration for textile wastewater treatment faces challenges such as fouling, which reduces efficiency and requires frequent maintenance, and high operational costs, particularly for energy intensive processes like reverse osmosis. Additionally, it often necessitates post-treatment steps and poses disposal issues for used membranes, complicating the treatment process and increasing costs [12].

Previous studies from Saad et al., [13] which integrated membrane with electrocoagulation which achieves a high dye removal efficiency of 79.4% optimized whereby an additional 10–30% of dye was removed. The research for integrated membranes to another wastewater treatment method significantly increase the efficacy treatment. However, there is no studies to comprehensively evaluated an integrated system that combines conventional processes with locally fabricated ceramic membranes tailored for the unique pollutant profile of songket wastewater. This work provides a novel, practical approach for small-scale industries by demonstrating the feasibility of a compact, locally-sourced treatment solution.

MATERIALS AND METHODS

Materials

The main sample used was songket textile wastewater. The chemical reagents used included

activated carbon (analytical grade), sodium hydroxide (NaOH 5N), hydrochloric acid (HCl), sulfuric acid (H₂SO₄), potassium iodide (KI), manganese sulfate (MnSO₄), starch indicator, pH buffer solution (6 and 8), and Whatman No. 42 filter paper. The materials for making ceramic membranes consisted of clay, iron powder, quartz sand, activated carbon, graphene oxide (GO), and distilled water.

Ceramic Membrane Fabrication

Two membrane formulations were prepared. The first consisted of 80% clay, 5% GO, 5% activated carbon, 5% quartz sand, and 5% iron powder; the second consisted of 80% clay, 5% quartz sand, and 10% activated carbon. All materials were mixed until homogeneous, molded using a press mold, dried, and sintered. The membranes were characterized using XRD, SEM, and FTIR.

Wastewater treatment integrated systems method

This study employed an integrated treatment methodology comprising sequential coagulation, adsorption-filtration, and ceramic membrane filtration in continuous flow systems. The sample was collected from songket industrials on Kampung Songket Tangga Buntung in Palembang City, which taken using the sample container volume capacity 20 L. Coagulation process utilized aluminum sulfate (Al₂(SO₄)₃·14H₂O) as the coagulant, with dosages ranging from 100 to 500 ppm.

The procedure involved rapid mixing at 120 rpm for 1 minute, followed by slow mixing at 20 rpm for 20 minutes, and a subsequent 15-minute settling period to determine the optimum coagulant dosage, which was then applied in a 10 L batch system on wastewater without filtering. The neutralized coagulated effluent was subsequently subjected to combined adsorption and filtration by pumping it through a column packed with activated carbon and a downstream polyurethane (PU) foam filter which the dimension form of the filtering is cylindrical fixed-bed adsorption column (5 cm inner diameter × 30 cm height, pore size of 20–50 microns (μm)).

The pre-treated wastewater underwent ceramic membrane filtration (Common tubular dimensions: 62 mm outer diameter, 42 mm inner diameter, 10 mm wall thickness; pores of 0.1–10 μm) at operating pressures ranging from 1 to 5 bar. Permeate samples were collected at 5-minute intervals over a 20-minute period for analysis on every stage method. The treatment efficacy for each stage was evaluated by analyzing key parameters: total suspended solids (TSS), pH, chemical oxygen demand (COD), and color using ASTM method.

RESULTS AND DISCUSSION

pH parameters

The pH variations in wastewater treated by three different methods adsorption, filtration, and membrane processes were analyzed to assess their effects on the acid-base balance of the wastewater. In this study, 50 grams of adsorbent material were used, and the treatment was conducted at a flow rate of 5 Lpm over varying durations of 5 to 90 minutes. As shown in **Figures 1** and **2**, the pH values of the treated water ranged from 6.90 to 7.07, indicating that all treatment processes maintained a relatively neutral and stable pH throughout the operation.

During the adsorption process, the pH remained almost constant, with minimal variation observed over time. This indicates that the adsorbent material did not significantly alter the pH of the wastewater. Such behavior is typical for carbon-based adsorbents, which are generally inert to changes in pH. In **Figure 1**, this stability in pH can be clearly observed, reflecting the inert nature of the adsorption process in terms of acid-base balance.

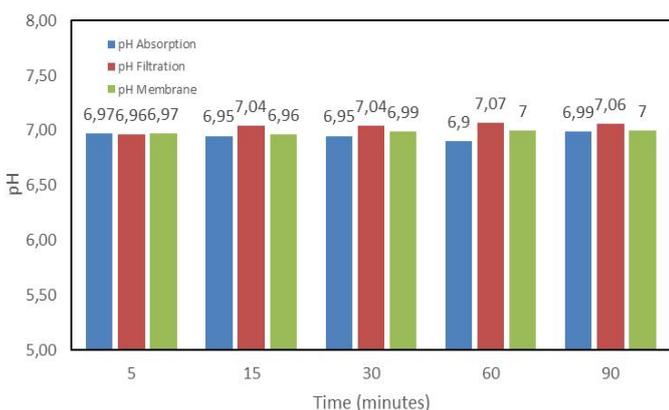


Figure 1. Condition of pH after complete treatment (adsorption, filtration and ceramic membrane)

Table 1. pH Data on Integrated Method Wastewater Treatment with Ceramic Membrane

Time (minutes)	pH		
	Adsorption	Filtration	Ceramic membrane
5	6.97 ± 0.091	6.96 ± 0.062	6.97 ± 0.054
15	6.95 ± 0.144	7.04 ± 0.083	6.96 ± 0.092
30	6.95 ± 0.144	7.04 ± 0.083	6.99 ± 0.094
60	6.9 ± 0.194	7.07 ± 0.102	7 ± 0.104
90	6.99 ± 0.172	7.06 ± 0.095	7 ± 0.175

The membrane process, as depicted in **Figure 2**, also exhibited stable pH values that remained close to neutral throughout the treatment. This result indicates

that the membrane separation process operated predominantly through physical mechanisms without significant chemical reactions, thus maintaining pH stability [14]. This stability is important for ensuring the performance and durability of the membrane material over time, as it prevents material degradation due to pH fluctuations.

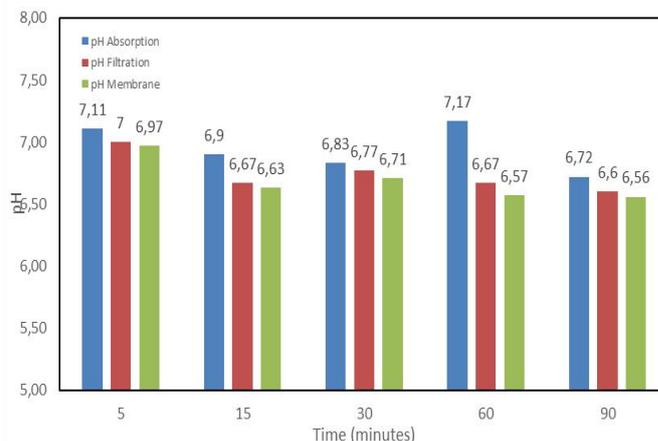


Figure 2. Condition of pH after complete treatment (adsorption, filtration and GO membrane)

Table 2. pH Data on Integrated Method Wastewater Treatment with GO Membrane

Time (minutes)	pH		
	Adsorption	Filtration	GO membrane
5	7.11 ± 0.05	7 ± 0.056	6.97 ± 0.071
15	6.9 ± 0.085	6.67 ± 0.04	6.63 ± 0.045
30	6.83 ± 0.107	6.77 ± 0.09	6.71 ± 0.13
60	7.17 ± 0.624	6.67 ± 0.08	6.57 ± 0.045
90	6.72 ± 0.045	6.6 ± 0.071	6.56 ± 0.089

In conclusion, all three treatment methods adsorption, filtration, and membrane processes successfully maintained a neutral pH range within the criteria required for wastewater quality standards. The minimal pH changes observed across these methods underscore their effectiveness in treating wastewater without compromising the pH balance, making them suitable for safe discharge into the environment [15]

Total Suspended Solids (TSS)

Figures 3 and **4** shows the decrease in Total Suspended Solids (TSS) concentration in songket wastewater after treatment through adsorption, filtration, and membrane processes at an adsorbent mass of 50 grams and a flow rate of 5 Lpm with a time variation of 5–90 minutes. Songket waste generally contains high suspended particles in the form of dye residues, textile fibers, and colloidal

solids, so it requires adequate contact time for optimal removal [16].

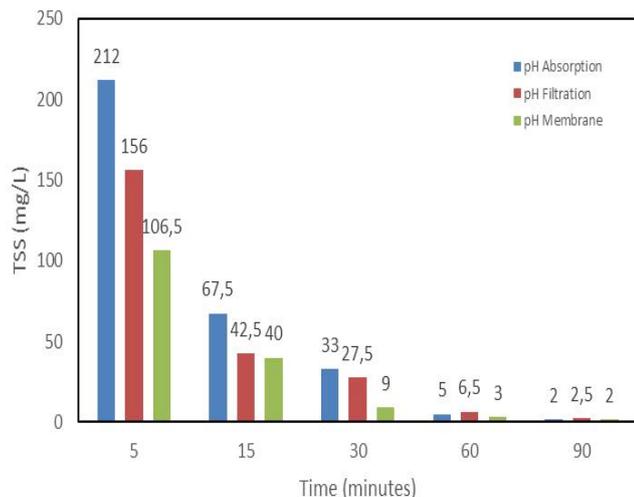


Figure 3. Condition of TSS after complete treatment (adsorption, filtration and ceramic membrane)

Table 3. TSS Data on Integrated Method Wastewater Treatment with Ceramic Membrane

Time (minutes)	TSS		
	Adsorption	Filtration	Ceramic membrane
5	212 ± 6	156 ± 2	106.5 ± 0.5
15	67.5 ± 4.5	42.5 ± 3.5	40 ± 4
30	33 ± 3	27.5 ± 6.5	9 ± 2
60	5 ± 2	6.5 ± 1.5	3 ± 0
90	2 ± 0	2.5 ± 0.5	2 ± 0

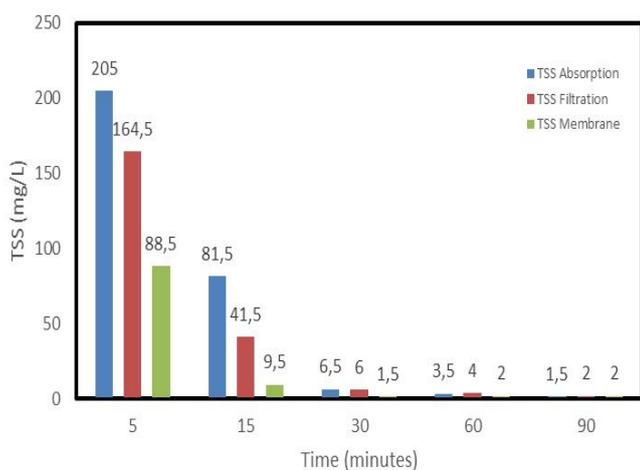


Figure 4. Condition of TSS after complete treatment (adsorption, filtration and GO membrane)

The results showed that TSS concentration decreased significantly with increasing operating time,

with removal efficiencies reaching approximately 99.1% (adsorption), 98.7% (filtration), and 99.1% (membrane) at 90 minutes compared to the initial conditions. A sharp decrease occurred until the 30th minute, especially in the membrane process which is able to selectively retain fine particles, while at 60–90 minutes the system tended to reach a condition close to equilibrium. This finding is consistent with reports indicating that the integration of adsorption, physical filtration, and membrane separation mechanisms is highly effective in diminishing TSS in textile and colored wastewater, thereby satisfying wastewater quality standards for discharge or subsequent treatment [16,17].

Table 4. TSS Data on Integrated Method Wastewater Treatment with GO Membrane

Time (minutes)	TSS		
	Adsorption	Filtration	GO membrane
5	205 ± 11	164.5 ± 8.5	88.5 ± 0.5
15	81.5 ± 3.5	41.5 ± 2.5	9.5 ± 0.5
30	6.5 ± 0.5	6 ± 1	1.5 ± 0.5
60	3.5 ± 1.5	4 ± 1	2 ± 1
90	1.5 ± 0.5	2 ± 1	2 ± 1

This trend is in line with the observed drop in TSS, which happens when longer contact times help particles stick to solid surfaces through adsorption, stay in place during filtration, and be rejected by the membrane. Simultaneous pH stabilization during treatment confirms that pollutant removal occurs primarily through physical and physicochemical mechanisms rather than chemical reactions that could disrupt the acid-base balance. Similar behavior has been widely reported in textile wastewater treatment studies, where combined adsorption-filtration-membrane systems effectively reduce organic and suspended solids loads while maintaining pH stability [18,19]

Chemical Oxygen Demand (COD)

The treatment performance of wastewater thru adsorption, filtration, and membrane processes was evaluated based on the variation of COD. The system was tested with an adsorbent mass of 50 grams and a flow rate of 5 Lpm, with a contact time ranging from 5 to 90 minutes. The results showed a strong correlation between increasing contact time and pollutant removal efficiency, while maintaining a stable pH condition close to neutral (pH 6.9–7.1), which is favorable for process stability and

downstream applications. Condition of COD after treatment shows in **Figure 5** and **6**.

COD concentrations decreased significantly from initial values of 118.41 (adsorption), 94.88 (filtration), and 68.71 mg/L (membrane) at 5 min to 4.12 mg/L, 4.29 mg/L, and 4.41 mg/L, respectively, at 90 min. This decrease corresponds to COD removal efficiencies of approximately 96.5% for adsorption, 95.5% for filtration, and 93.6% for the membrane process. The most significant COD reduction occurred within the first 30 min, indicating the rapid removal of easily oxidized organic compounds commonly present in textile wastewater, such as dyes and auxiliaries [20].

Overall, the integrated treatment system demonstrated high efficiency in reducing COD and TSS while maintaining a neutral pH, confirming its suitability as an advanced treatment strategy capable of meeting wastewater discharge standards and supporting sustainable textile wastewater management.

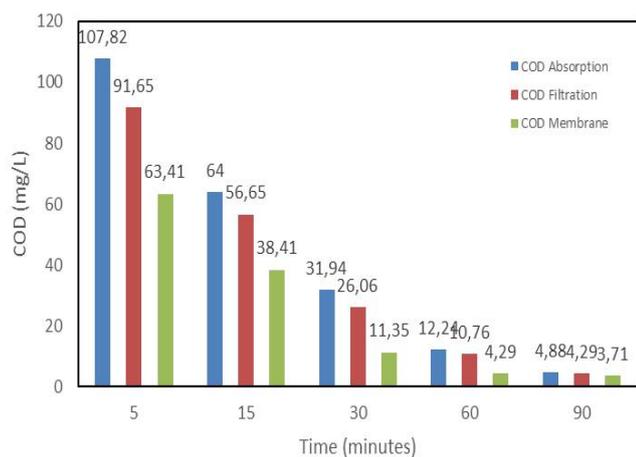


Figure 5. Condition of COD after complete treatment (adsorption, filtration and ceramic membrane)

Table 5. COD Data on Integrated Method Wastewater Treatment with Ceramic Membrane

Time (minutes)	COD		
	Adsorption	Filtration	Ceramic membrane
5	107.82 ± 3.744	91.65 ± 2.496	63.41 ± 3.328
15	64 ± 3.328	56.65 ± 3.744	38.41 ± 2.912
30	31.94 ± 3.744	26.06 ± 1.248	11.35 ± 2.912
60	12.24 ± 1.664	10.76 ± 1.248	4.29 ± 1.248
90	4.88 ± 0.416	4.29 ± 0.416	3.71 ± 0.416

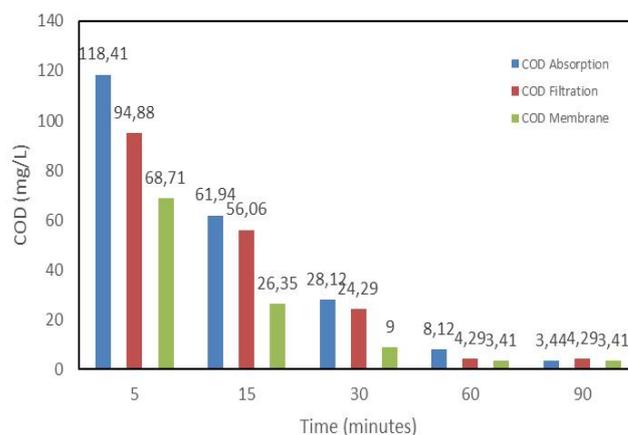


Figure 6. Condition of COD after complete treatment (adsorption, filtration and GO membrane)

Table 6. COD Data on Integrated Method Wastewater Treatment with GO Membrane

Time (minutes)	COD		
	Adsorption	Filtration	GO membrane
5	118.41 ± 2.08	94.88 ± 2.08	68.71 ± 9.151
15	61.94 ± 0.416	56.06 ± 1.248	26.35 ± 2.496
30	28.12 ± 1.664	24.29 ± 1.248	9 ± 0.416
60	8.12 ± 0.832	4.29 ± 0.416	3.41 ± 0
90	3.41 ± 0	4.29 ± 0.416	3.41 ± 0

Color

Color is an important parameter in assessing water quality because it indicates the presence of contaminants such as organic compounds, heavy metals, and synthetic dyes that can reduce aesthetics and endanger health. **Table 1** shows the color parameters for each treatment stage performed, with the Pt-Co value reflecting a significant reduction in color intensity.

Table 7. Color Parameter Table

NO.	Research Sample	Color (Pt-Co)	SNI 6989.80:2011
1	Initial Waste	976.5	≤150
2	After Coagulation	181.5	≤150
3	After Adsorption	71.8	≤150
4	After Filtration	35.2	≤150
5	After Membrane	10.6	≤150

Drinking water has a maximum limit of 15 TCU according to the Indonesian Minister of Health

Regulation No. 492/2010, while the color quality standard for textile industry wastewater is ≤ 150 TCU based on the Minister of Environment and Forestry Regulation No. 68/2016. Songket industry waste generally contains synthetic, reactive, disperse, acidic, or alkaline dyes that are toxic, difficult to decompose, and can affect the pH and balance of aquatic ecosystems. Therefore, proper treatment is necessary before discharge to prevent further environmental pollution.

CONCLUSION

Integrated treatment of songket dyeing wastewater through coagulation, adsorption, filtration, and ceramic membrane filtration has been proven effective in significantly reducing key pollutant parameters such as color, Total Suspended Solids (TSS), and Chemical Oxygen Demand (COD), which are typical indicators of textile wastewater pollution. Coagulation using aluminum sulfate effectively destabilizes colloidal particles and reduces turbidity, thereby increasing the efficiency of subsequent treatment stages. While adsorption using activated carbon plays a crucial role in removing dissolved dyes and organic compounds through physical and chemical interactions on the adsorbent surface. The filtration process further removes residual suspended solids, and ceramic membrane filtration provides advanced separation capabilities for fine particles and dissolved contaminants, resulting in high-quality wastewater suitable for discharge. The relatively stable pH observed throughout the treatment process indicates that pollutant removal occurs primarily through physical and physicochemical mechanisms without causing adverse chemical effects on the treated water. Overall, the combined coagulation–adsorption–filtration–ceramic membrane system is capable of producing treated wastewater that meets or approaches Indonesian textile wastewater quality standards and shows strong potential as an environmentally friendly and sustainable treatment alternative for small to medium-scale textile industries.

ACKNOWLEDGMENT

The author would like to thank the Direktorat Penelitian dan Pengabdian Kepada Masyarakat Direktorat Jendral Riset dan Pengembangan Kementerian Pendidikan Tinggi, Sains dan Teknologi (Grant No. 109/C3/DT.05.00/PL/2025) for financial support of this work.

REFERENCES

- [1] N.K.T. Martuti, I. Hidayah, M. Margunani, and R. B. Alafima, "Organic Material for Clean Production in the Batik Industry: A Case Study of Natural Batik Semarang, Indonesia," *Recycling*, vol. 5, no. 4, p. 28, Oct. 2020.
- [2] N.Y. Donkadokula, A.K. Kola, I. Naz, and D. Saroj, "A review on advanced physico-chemical and biological textile dye wastewater treatment techniques," *Reviews in Environmental Science and Bio/Technology*, vol. 19, no. 3, pp. 543–560, Sep. 2020.
- [3] M.B. Ceretta, D. Nercessian, and E.A. Wolski, "Current Trends on Role of Biological Treatment in Integrated Treatment Technologies of Textile Wastewater," *Front. Microbiol.*, vol. 12, Mar. 2021.
- [4] M.B. Hoque, T.H. Oyshi, M.A. Hannan, P. Haque, M.M. Rahman, M.A. Shahid, S. Sheikh, "Unraveling the ecological footprint of textile dyes: A growing environmental concern," *Pollution Study*, vol. 5, no. 2, p. 3014, Dec. 2024.
- [5] A. Azanaw, B. Birlie, B. Teshome, and M. Jemberie, "Textile effluent treatment methods and eco-friendly resolution of textile wastewater," *Case Studies in Chemical and Environmental Engineering*, vol. 6, p. 100230, Dec. 2022.
- [6] S.B. Kurniawan, A. Ahmad, M.F. Imron, S.R. S. Abdullah, A.R. Othman, and H.A. Hasan, "Achieving a Biocircular Economy in the Aquaculture Sector Through Waste Valorization," *Toxics*, vol. 13, no. 2, p. 131, Feb. 2025.
- [7] A.S. Reddy, S. Kalla, and Z.V.P. Murthy, "Textile wastewater treatment via membrane distillation," *Environmental Engineering Research*, vol. 27, no. 5, pp. 210228–0, Sep. 2021..
- [8] K.C. Khulbe and T. Matsuura, "Removal of heavy metals and pollutants by membrane adsorption techniques," *Applied Water Science*, vol. 8, no. 1, p. 19, Mar. 2018.
- [9] Kouzi, Z.C. Elidrissi, A. Essate, D. Beqqour, B. Achiou, S.A. Younsi, M. Rabiller-Baudry, M. Bouhria, M. Ouammou, "Tailored rGO-TiO₂-PPD low-cost ceramic membrane for dye wastewater filtration: A synergistic strategy of GO reduction, intercalation and crosslinking," *Separation and Purification Technology* Vol. 378, no. 3, Dec 2025.
- [10] J. Bahrouni, F. Aouay, C. Larchet, L. Dammak,

- R.B.Amar, "Eco-Friendly Ceramic Membranes from Natural Clay and Almond Shell Waste for the Removal of Dyes and Drugs from Wastewater," *Membranes*, vol. 16, no. 2, p. 52, 2026.
- [11] J. Bahrouni, A. Attia, F.Z. Elberrichi, L. Dammak, L. Baklouti, M.A.B. Aissa, R.B. Amar, A. Deratani, "Green and Sustainable Clay Ceramic Membrane Preparation and Application to Textile Wastewater Treatment for Color Removal," *Membranes (Basel)*, vol. 15, no. 10, p. 292, Sep 2025.
- [12] E.O. Ezugbe and S. Rathilal, "Membrane Technologies in Wastewater Treatment: A Review," *Membranes*, vol. 10, no. 5, p. 89, 2020.
- [13] M.S. Saad, L. Balasubramaniam, M.D.H. Wirzal, N.S.A. Halim, M.R. Bilad, N.A.H.M. Nordin, Z.A. Putra, F.N. Ramli, "Integrated Membrane-Electrocoagulation System for Removal of Celestine Blue Dyes in Wastewater," *Membranes*, vol. 10, no. 8, p. 184, 2020.
- [14] I. Hegoburu, K. L. Zedda, and S. Velizarov, "Treatment of Electroplating Wastewater Using NF pH-Stable Membranes: Characterization and Application," *Membranes (Basel)*, vol. 10, no. 12, p. 399, Dec. 2020.
- [15] J. Makulec, A. Chrzanowska, P. Siudem, and K. Paradowska, "Literature Review on Adsorption Efficiency of Paracetamol on Different Adsorbent Materials," *International Journal of Molecular Sciences*, vol. 27, no. 2, p. 623, Jan. 2026.
- [16] R. Ardianto, G. Samudro, S. Mangkoedihardjo, and S. T. Isratul Izmi, "Integrated approach to textile wastewater treatment: Investigating electrocoagulation, MBBR, and adsorption synergy," *Journal of Water Process Engineering*, vol. 77, p. 108364, Sep. 2025.
- [17] K.C. Chong, S.O. Lai, W.C. Chong, Y L. Pang, S.K. Mah, and J.H. Teong, "Industrial Textile Wastewater Treatment by Crossflow NF Membrane Filtration," *Journal of Applied Membrane Science & Technology*, vol. 27, no. 3, pp. 111–117, Nov. 2023.
- [18] A. Azanaw, B. Birlie, B. Teshome, and M. Jemberie, "Textile effluent treatment methods and eco-friendly resolution of textile wastewater," *Case Studies in Chemical and Environmental Engineering*, vol. 6, p. 100230, Dec. 2022, doi: 10.1016/j.cscee.2022.100230.
- [19] Q.H. Tan, K.C. Chong, W.C. Chong, S.O. Lai, S.H. Shuit, and S. Lim, "Evaluating the Separation Performance and Efficiency of MF Membranes in Industrial Textile Wastewater Treatment," *Journal of Applied Membrane Science & Technology*, vol. 28, no. 3, pp. 9–16, Dec. 2024.
- [20] A. Murniati, N.A. Fajriana, G.A. Nugraha, R.M. Ibrahim, A. Hardian, B. Buchari, S. Gandasasmita, Z. Nurachman, "Textile Wastewater Treatment Using Polypyrrole/Polyphenol Oxidase Membranes," *Jurnal Kimia Sains dan Aplikasi*, vol. 27, no. 2, pp. 83–90, Apr. 2024.