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Green Alternatives to Chemical Coagulants: Cactus and Spinach Bioflocculants for Textile Wastewater Traetment.

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Abstract

The intensive use of chemical coagulants in textile wastewater treatment raises environmental and health concerns related to toxic residues and non-biodegradable sludge. This study investigates the efficiency of plant-based bioflocculants derived from *Opuntia ficus-indica* (cactus) and *Spinacia oleracea* (spinach) as sustainable alternatives to conventional chemical agents for textile effluent treatment. Cactus gel, cactus powder, and spinach powder were prepared, characterized, and applied either alone or in hybrid systems with aluminum sulfate and the synthetic flocculant Preastol 2539. Experiments were conducted on real textile wastewater collected from the Sebdou industrial zone (Algeria). Treatment performance was evaluated through turbidity and chemical oxygen demand (COD) removal, as well as changes in physicochemical parameters. The chemical control achieved the highest removal efficiencies (91.48% turbidity and 71.53% COD). However, spinach powder used in hybrid mode reached comparable turbidity removal (91.18%) with substantial COD reduction (66.34%). Cactus gel and cactus powder also demonstrated high turbidity abatement (up to 89.95%), particularly under optimized dosage and salinity conditions. The results confirm that plant-based bioflocculants, especially spinach powder, can significantly reduce reliance on synthetic reagents while maintaining high treatment efficiency. These findings support the integration of locally available, biodegradable materials into sustainable textile wastewater management strategies

Keywords: Textile industrial effluents, bioflocculant, cactus, turbidity, spinach, COD.

Introduction

Air, water, and soil pollution, along with waste management and other environmental issues, must be urgently addressed. (Ozunu et al. 2024) Water is an essential element for life and for the real and sustainable socio-economic development of a country. (Westall and Brack 2018; Ugrina and Milojković 2024) The growing challenges related to water availability have led to stricter environmental regulations, including those governing the discharge of industrial wastewater. It is therefore essential to improve and develop cost-effective wastewater treatment methods and to encourage water reuse. (Mukandi et al. 2024)

Today, environmental protection has become a major issue for humanity. Wastewater containing dyes is a major pollutant, posing risks not only to the environment but also to human health, as textile industries generate large quantities of highly colored wastewater containing various persistent pollutants. (Ali 2022; Ayat and Gouda 2025) The composition of these effluents varies over time and across facilities, and they may contain high concentrations of suspended solids, heavy metals, dyes, and surfactant molecules. (Ali and Mansor 2020; Khelassi-Sefaoui and al. 2021) Textile wastewater is typically characterized by high color intensity due to residual dyes that fail to fix to fibers during dyeing processes.

(Khelassi-Sefaoui and al. 2025) In industrial dyeing, a significant proportion of the dye often overdosed to improve fixation is released into water bodies. Since these dyes are poorly biodegradable, they tend to accumulate in the environment, posing considerable toxicity risks to living organisms. This highlights the urgent need to develop specific decontamination processes to protect water resources. (Robinson et al. 2001; Forgacs et al. 2004; Khatri et al. 2015)

Chemical oxygen demand (COD) is often extremely high in organic emulsions from textile discharges, while mineral emulsions are highly turbid, toxic, and conductive. (Ali and Mansor 2020; Khelassi-Sefaoui and al. 2021) Conventional methods used for removing dyes from industrial wastewater typically include biological and physicochemical treatments, or combinations of both. (Al-a'qarbeh et al. 2020)

Flocculation is a key process used for removing suspended solids in both domestic and industrial wastewater treatment. This process involves the use of flocculants either natural or synthetic agents that promote particle aggregation into flocs. (Agunbiade et al. 2016) Inorganic and synthetic flocculants are commonly applied in dye-containing wastewaters. However, they pose risks to both the environment and human health; for example, acrylamide is known to have neurotoxic and carcinogenic effects. (Artifon et al. 2021) These flocculants also generate hazardous activated sludge containing residual aluminum, which may lead to adverse effects once released into natural water bodies. (Badawi et al. 2023)Studies have shown that long-term exposure to high levels of aluminum can cause serious illnesses such as Alzheimer's disease. (Campbell 2002) The use of plant-derived bio-coagulants presents a promising pathway for establishing sustainable and environmentally responsible water treatment solutions. These natural agents are not only renewable and affordable but can also be sourced and processed locally, making them highly accessible for widespread application. Unlike conventional synthetic coagulants, they produce non-toxic sludge that poses no risk to human health or the ecosystem. Moreover, this residual biomass can be safely managed through biological degradation or beneficial reuse such as soil amendment due to its biodegradable and harmless nature. (Adachi et al. 2023)

Therefore, there is a pressing need to develop bio-flocculants as alternative products that are safer for the environment, more efficient, and more economical while offering performance comparable to chemical flocculants. (Li et al. 2020; Ajao et al. 2021)Moreover, the extraction of bio-flocculants is simple and accessible. Among the most studied bio-flocculants for treating surface water turbidity and industrial liquid effluents, natural plant-based flocculants in gel or powder form show potential for removing suspended sludge while allowing for sludge reuse and treated water recycling, due to their non-toxic nature. (Madera-Santana et al. 2018 ;García Martín and al. 2024)

In this context, several natural materials derived from seeds, fruits, and leaves such as linden seeds (Seghosime et al. 2017), tamarind seed pods (Buenaño et al. 2019), oak leaves (Benalia et al. 2018), cactus pads (Kumar 2000), banana peels (Zaidi et al. 2019) , and hyacinth beans (Shilpa and 2012)have been explored. This study investigates the use of a natural, biodegradable, and non-toxic flloculant in a semi-industrial coagulation–flocculation process, focusing on cactus leaves as a readily available and renewable resource in Algeria. (Benalia et al. 2026)Rich in polysaccharides, mainly mucilage and pectin, cactus extracts exhibit significant coagulating properties, effectively destabilizing suspended particles. Importantly, these extracts are biodegradable, non-toxic, and environmentally friendly compared to conventional chemical coagulants. In line with recent research on natural flocculants for water and wastewater treatment, particularly for dye removal, this work explores the use of a new biodegradable organic flocculant extracted from cactus juice within a physicochemical coagulation–flocculation process to treat textile effluents. Given these advantages, replacing synthetic chemical coagulants and flocculants with effective, environmentally safe natural alternatives should be considered a priority.

The main objective of this work is to gain a better understanding of the capabilities and limitations of bio-flocculation processes using natural flocculants. Specifically, we aim to assess the effectiveness of three different types of plant-based bio-flocculants cactus gel, cactus powder, and spinach powder for the treatment of textile wastewater. The study also includes a comparative evaluation of these natural agents against conventional chemical flocculants currently used in the SEBDOU textile industry, with a focus on their ability to reduce turbidity and chemical oxygen demand (COD). This study introduces an innovative comparative approach by evaluating these green agents both individually and in synergy with conventional flocculants (aluminum sulfate and Preastol 2539), applied to real effluents from the Sebdou textile industry. The originality of this study lies in the valorization of locally available plant-based materials as effective and biodegradable alternatives to synthetic reagents, and in the integration of physicochemical treatment with eco-friendly flocculants.

Materials and methods

Wastewater from the textile industry

Three wastewater samples were collected at the inlet of the treatment plant of a textile factory located in EATIT Sebdou-Tlemcen, Algeria, where the effluents are treated using conventional processes before being discharged into the Tafna River. Textile effluents not only contain residual dyes but also various chemical additives such as thickeners, surfactants, and finishing agents. A significant portion of these substances is not retained on the textile fibers and is therefore released into the wastewater stream. To prevent degradation of the compounds during storage and transportation, standard sampling protocols were strictly followed. The samples were transported in cooled containers and stored at 4 °C until analysis. (Rice et al. 2017; Torres et al. 2019) Field parameters such as pH and temperature were measured on-site, while

other physicochemical characteristics were determined in the laboratory following standard analytical procedures. (Torres et al. 2019) The characteristics of the raw textile wastewater are presented in Table 1.

The analysis of the three textile wastewater samples revealed high turbidity, conductivity, COD, and extreme pH values, indicating significant pollution. Sample N°1, collected in February during white fabric production, contained only chemical additives and auxiliaries. Samples N°2 and 3, taken in March and April during colored fabric production, included dyes in addition to chemicals and auxiliaries, resulting in higher pollution loads. Only pH in Sample N°2 remained within WHO limits, (WHO 2017)while COD in all samples greatly exceeded national and international discharge standards. The high turbidity and conductivity levels confirm the presence of suspended solids and salts. Commonly associated with textile effluents. (Rafiqul islam and Mostafa 2020; Worku and Abate 2025) These results underscore the urgent need for advanced and integrated treatment processes such as bioflocculation, membrane filtration, or algal-based systems prior to environmental discharge. (Kato and Kansha 2024)

Table 1 Physicochemical characteristics of raw textile wastewater collected from the EATIT-SEBDOU industry (Algeria)

Parameters	Sample N°1	Sample N°2	Sample N°3
Turbidity (NTU)	526.1	968	975.9
Conductivity (µS/cm)	2300	1000	1727
pH	6.68	8.20	10.73
Temperature (°C)	24	23	22.9
COD (mg/L)	1133	1200.68	1103

Bioflocculants

Preparation of Cactus Gel

Bioflocculants are extracellular molecules produced by microorganisms. Their biosynthesis is linked to cellular adhesion on surfaces, facilitating biofilm formation. As a result, these components exhibit strong environmental resistance and high adsorption capacity. (Nouha et al. 2018)Cactus is a succulent xerophytic plant capable of storing large amounts of water. (Nouha et al. 2018)This plant can be used in a wide range of wastewater treatment applications. (Abid et al. 2009; Li et al. 2020) The cactus used in this study was collected from the Sebdou-Tlemcen region in Algeria. The extraction of plant-based bioflocculants for wastewater treatment represents a key advancement in the development of environmentally friendly and sustainable technologies. Two extraction methods were applied for cactus-based bioflocculants: (a) solvent extraction followed by precipitation, and (b) drying and grinding. (Lee et

al 2014) The physicochemical characteristics of the cactus are presented in Table 2. The extract was diluted in water at different concentrations (5%, 10%, and 15%) and stirred for 15 to 20 minutes to ensure homogenization. The resulting mixture remained stable and retained its flocculating power for several days. Finally, it was stored in a sterilized glass bottle.



Fig. 1 Preparation of diluted and concentrated cactus gel

Table 2 The physicochemical characteristics of concentrated cactus gel

Compound	pH	Conductivity (mS/cm)	Density	Moisture Content (%)	λ_{max} (nm)
concentrated cactus gel	4.83	9.63	1.164	93.363	300

Preparation of Cactus and Spinach Powders

Fresh spinach leaves (*Spinacia oleracea*) were harvested in February from the Maghnia-Tlemcen region in Algeria. The collected leaves were carefully washed with distilled water to eliminate soil particles and surface contaminants. After cleaning, the spinach was drained and spread out in a single layer in a shaded, well-ventilated area, protected from direct sunlight, and left to air dry for approximately 4 weeks. This method helps preserve the phytochemical and functional properties of the leaves. Once completely dried, the spinach was crushed and finely ground using a mortar. The resulting powder was then sieved to obtain a uniform particle size. The spinach powder was stored in clean, sterilized containers under dry conditions to prevent moisture absorption and microbial growth, making it ready for application as a natural coagulant in wastewater treatment as shown in Figure 2.



Fig. 2 Spinach powder preparation steps.

Fresh cactus pads were collected from the Sebdou-Tlemcen region in Algeria. The selected cactus samples were thoroughly washed with clean water to remove dust, dirt, and surface impurities. After cleaning, the pads were cut into small uniform pieces to facilitate drying. The pieces were then dried in a shaded, well-ventilated area, away from direct sunlight, for a period of 4 weeks in order to preserve their bioactive components. Once fully dried, the cactus pieces were ground using mortar until a fine green powder was obtained as represented in Figure 3. The powder was then sieved to ensure uniform particle size and stored in sterilized, airtight containers to protect it from moisture and contamination until further use in wastewater treatment experiments.



Fig. 3 Cactus powder preparation steps.

Preparation of Plant Powder/Saline Solution Mixtures

Mixtures of cactus powder and spinach powder with saline solution were prepared at different concentrations, as detailed in Table 3. For example, to prepare a mixture at 20 g/L using a 0.1 M saline solution, 20 g of either cactus or spinach powder was dissolved in 1 L of the saline solution. Each mixture was then homogenized by continuous stirring for 2 hours at room temperature to ensure proper dispersion of the plant powders in the saline medium. These mixtures were subsequently used in tests to evaluate their effectiveness as bioflocculants in wastewater treatment

Table 3 Preparation of Plant Powder/Saline Solution Mixtures

Saline solution concentration	Plant powder concentration (g/L)	
	Cactus (g) / Saline Solution (L)	Spinach (g) / Saline Solution (L)
0.1M	20	20
	40	40
0.7M	20	20
	40	40
1.3M	20	20
	40	40

Wastewater treatment procedure using cactus gel

Five 100 mL Erlenmeyer flasks were filled with untreated wastewater (Sample N°1). Each flask was subjected to a different treatment protocol as follows:

- **Flask 1**: Served as the reference, in which the chemical coagulant and flocculant commonly used at the Sebdou textile plant were added.
- **Flask 2**: Received the chemical coagulant combined with diluted cactus gel.
- **Flask 3**: Received the chemical coagulant and concentrated cactus gel.
- **Flask 4**: Received the chemical coagulant and a higher dose of the diluted cactus gel.
- **Flask 5**: Received the chemical coagulant along with a mixture of the chemical flocculant and the diluted cactus-based bio-flocculant.

All mixtures were stirred under identical conditions to ensure homogenization and effective interaction between coagulants/flocculants and the wastewater contaminants. The same experimental protocol was replicated using Sample N°2 of the textile wastewater to evaluate the reproducibility and efficiency of the treatment process under different effluent conditions (see Figures 4 and 5).

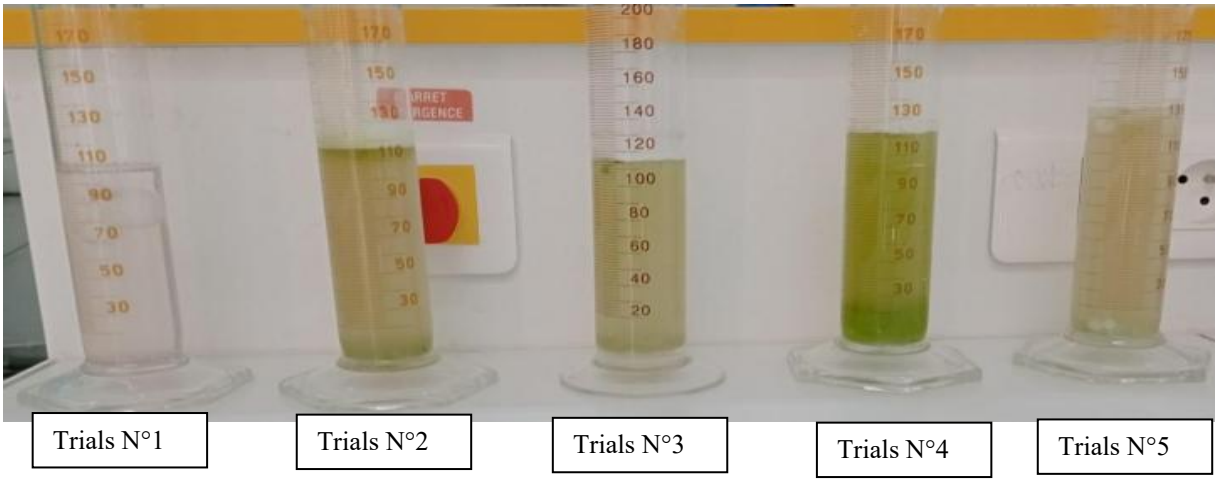


Fig. 4 reatment trials of wastewater (Sample N°1) using cactus gel

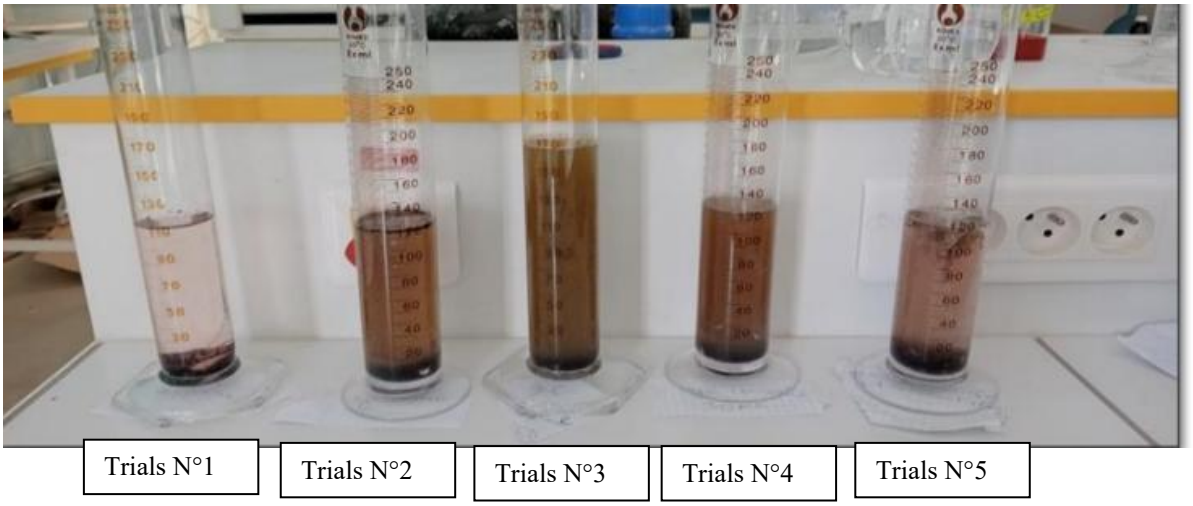


Fig. 5 Treatment trials of wastewater (Sample N°2) using cactus gel

Wastewater treatment procedure using cactus and spinach powders

In Figure 6, three sets of experiments were conducted using saline solutions at different concentrations: 0.1 M, 0.7 M, and 1.3 M. For each saline concentration, five treatment trials were performed according to the following protocol:

Five 100 mL Erlenmeyer flasks were each filled with wastewater (Sample N°3). The treatments were applied as follows: (see Table 4), The same experimental protocol was replicated using spinach powders.

Table 4 Experimental Protocols for Wastewater Treatment Using Spinach-Based Bio-Flocculant

Trials N°	Saline solution concentration	Treatment type	Amount of bioflocculant	Components Added
1		Control (Conventional)		Chemical coagulant + Chemical flocculant (as used in the Sebdou textile unit)
2		Bio-flocculant (V_1, C_1)	V_1=5ml	Chemical coagulant + Spinach-based bio-flocculant (V_1, C_1)
3	0.1,0.7 or 1.3	Hybrid Treatment(V_2,C_1)	V_2=10ml C_1=20g/l C_2=40g/l	Chemical coagulant + Spinach-based bio-flocculant (V_2, C_1) + Chemical flocculant
4		Bio-flocculant (V_1, C_2)		Chemical coagulant + Spinach-based bio-flocculant (V_1, C_2)
5		Hybrid Treatment(V_2, C_2)		Chemical coagulant + Spinach-based bio-flocculant (V_2, C_2) + Chemical flocculant

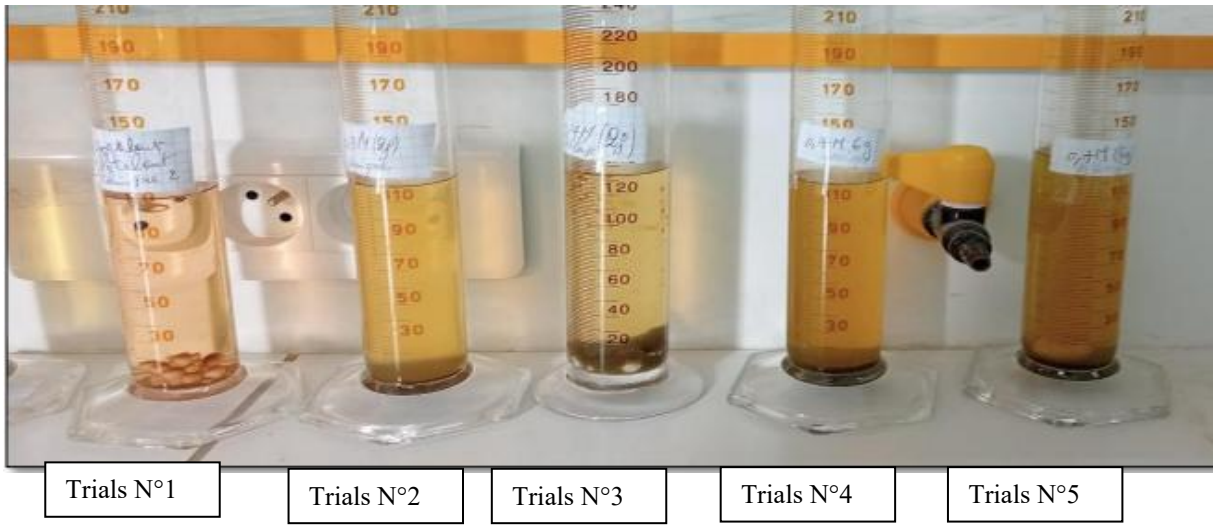


Fig. 6 Wastewater treatment trials (Sample N°3) using spinach powder with a saline solution concentration of 0.7 M

Analytical method

The efficiency of textile wastewater treatment was comprehensively assessed by evaluating key parameters, including turbidity reduction, chemical oxygen demand (COD) removal, and changes in optical properties through spectrophotometric monitoring. These parameters were selected to assess not only the visual clarity of the effluent but also the effectiveness of organic pollutant removal achieved through the use of natural bioflocculants extracted from cactus and spinach. Turbidity measurements were performed using an Orbeco-Hellige turbidimeter (TBMT-M10-001 METRIA model M10), in accordance with standard nephelometric techniques. This allowed for quantification of suspended particulate matter and colloids in the effluent before and after treatment, serving as a direct indicator of flocculation efficiency. (Mels et al. 2004) The percentage of turbidity removal was calculated using the following formula:

$$\text{Turbidity removal}(\%) = \frac{T_0 - T_f}{T_0} \times 100 \quad (1)$$

where T_0 and T_f represent the turbidity values before and after treatment, respectively.

COD was measured using the standard closed reflux method, followed by titrimetric determination, a widely recognized method in water quality analysis. (APHA 2017) The reduction in COD values provided a measure of the biodegradability of the treated effluent and the extent of pollutant removal achieved by the bioflocculants. The COD removal efficiency was determined using the formula:

$$\text{COD}(\%) = \frac{C_0 - C_f}{C_0} \times 100 \quad (2)$$

where C_0 and C_f are the COD concentrations before and after treatment, respectively. These calculations provided insight into the extent of pollutant removal achieved by the bioflocculants.

UV-visible spectrophotometry (SP-UV 2005) was employed to determine the maximum absorbance wavelength (λ_{max}) of the untreated wastewater, which served as a fingerprint for dye and organic pollutant presence. Furthermore, the optical density of cactus gel solutions was monitored over time to study their behavior and stability under operational conditions. Absorbance scans were recorded across a wavelength range of 200–900 nm to detect spectral shifts or intensity changes, which could signal molecular interactions, degradation of chromophores, or formation of by-products. Physico-chemical parameters such as pH and electrical conductivity (EC) were also recorded to monitor the impact of the treatment process on effluent quality. pH was measured using an Adwa AD1030 pH/mV & Temperature

Meter, ensuring accurate assessment of acid-base shifts during flocculation. EC measurements were carried out using a conductivity meter (Adwa, AD3000) to assess changes in ionic strength and the presence of dissolved solids. All experimental trials were conducted in triplicate to ensure reproducibility and minimize random error. Mean values were reported for each parameter, and data were presented graphically to illustrate trends and variability. This multi-parameter analytical framework enabled a robust evaluation of treatment performance, providing evidence of the efficacy of cactus- and spinach-based bioflocculants in improving the quality of textile industrial effluents by targeting both suspended solids and organic contaminants.

Results and discussion

Wastewater treatment using cactus gel

Effect of cactus gel concentration

The results presented in Table 5 and figure 7 clearly demonstrate the major influence of cactus gel concentration and application mode on turbidity reduction performance in wastewater treatment. In the first series of tests (with 15 mL of cactus gel combined with the conventional coagulant), turbidity reduction followed a non-linear trend, showing significant improvement at 5% and 10%, followed by a sharp deterioration at 15%. This observation supports the hypothesis that overdosing bio-flocculants can lead to the destabilization of colloidal particles, thereby impairing the coagulation–flocculation process and promoting particle re-suspension. This sharp rise may be attributed to the overdosing of bio-flocculant, which could destabilize colloidal particles rather than promoting aggregation, leading to re-suspension phenomena. Similar overdosing effects have been reported in prior studies using natural coagulants. (Yin 2010)

Table 5 Effect of cactus gel concentration on turbidity

	Coagulant +Cactus gel (15ml)	Coagulant +Cactus gel (7ml)+ flocculant chimique (7ml)	
Trials	N°1	N°2	N°3
			N°4
			N°5
			N°6
	Cactus gel concentration		
	5 %		
	10%		

15%

5%

10%

15%

Turbidity (NTU)

84

72

613

41.98

22.13

233

The combination of cactus gel with flocculant significantly improved turbidity removal, reaching the lowest value at 10% concentration. However, performance declined at 15%, confirming the importance of optimizing dosage. These results emphasize the synergistic effect of hybrid systems and support previous findings on the dose-dependent nature of plant-based coagulants like *Opuntia ficus-indica*. (Miller et al 2008)

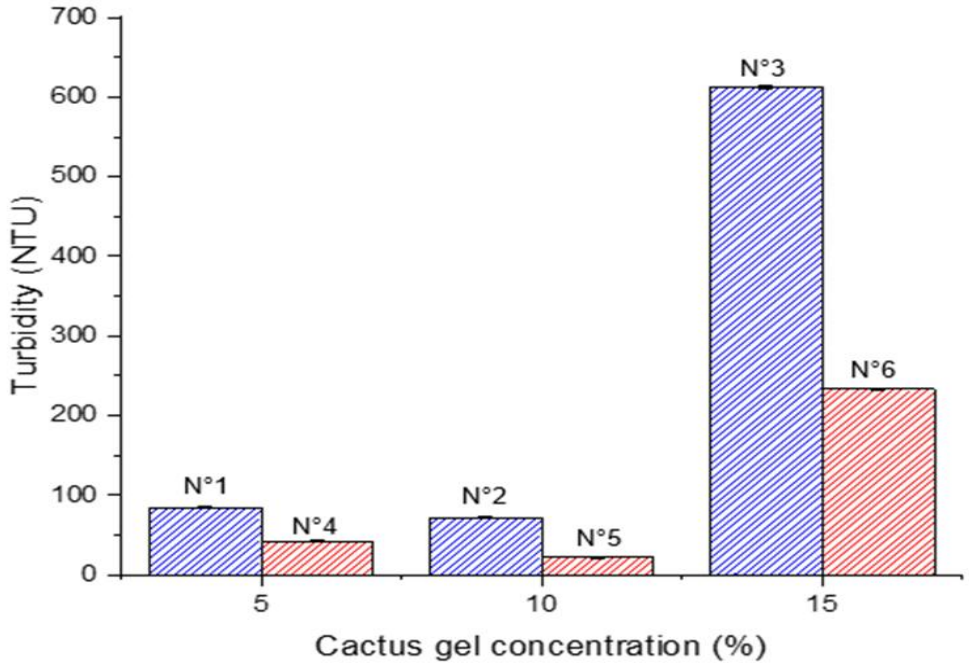


Fig. 7 Variation of turbidity as a function of cactus gel concentration

Effect of the optimal volume of added cactus gel

Figure 8 illustrates the influence of increasing treatment volume (in mL) on the turbidity of the treated wastewater. The data reveal a clear inverse relationship between the applied volume and the resulting turbidity up to a certain threshold, beyond which turbidity begins to increase again. At lower volumes (2–6 mL), the system shows high turbidity values, with 538 NTU at 2 mL and 510 NTU at 4 mL. This indicates insufficient coagulant/flocculant dosage, leading to poor particle aggregation and ineffective sedimentation. As the volume increases to 12 and 15 mL, turbidity drops significantly to 112 and 68 NTU respectively, demonstrating optimal particle destabilization and floc formation conditions often associated with the optimal dose of natural bio-flocculants. However, beyond 15 mL, turbidity begins to rise again, reaching 96 NTU at 18 mL and 136 NTU at 20 mL. This trend suggests a phenomenon of overdosing, where excessive bio-flocculant leads to restabilization of colloidal particles or formation of excessively light and unstable flocs that resist sedimentation. Such behavior is well-documented in the literature for plant-based coagulants, where maintaining a dosage within an optimal range is critical for efficient turbidity removal. (Yin 2010; Adachi et al. 2023)The effectiveness of cactus gel increases progressively with the addition of flocculant, reaching a maximum at a volume of 15 mL, corresponding to a turbidity reduction rate of 92.98%. Beyond this dose i.e., in the case of overdosing the turbidity removal efficiency decreases, which can be explained by steric destabilization of colloidal particles.

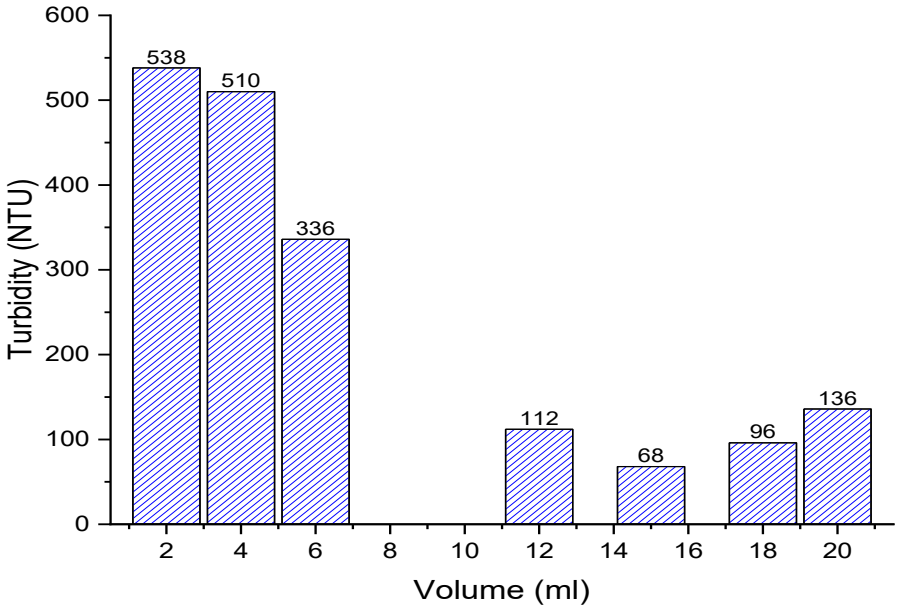


Fig. 8 Effect of the volume of cactus gel added

Cactus gel treatment applied to Sample N°1

In order to determine the optimal working combination (coagulant/cactus gel) for the coagulation–flocculation treatment process, tests were conducted using chemical reagents such as aluminum sulfate and Preastol 2539, which are commonly applied in the physicochemical treatment of industrial effluents at the Sebdou plant. The treatment of the solution (Sample N°1) was carried out through five different combinations, labeled from 1 to 5, with the experimental temperature maintained at approximately 25 °C and the pH adjusted to 3.5. The trials were then allowed to settle, and the resulting turbidity and COD values are presented in Figures 9 and 10.

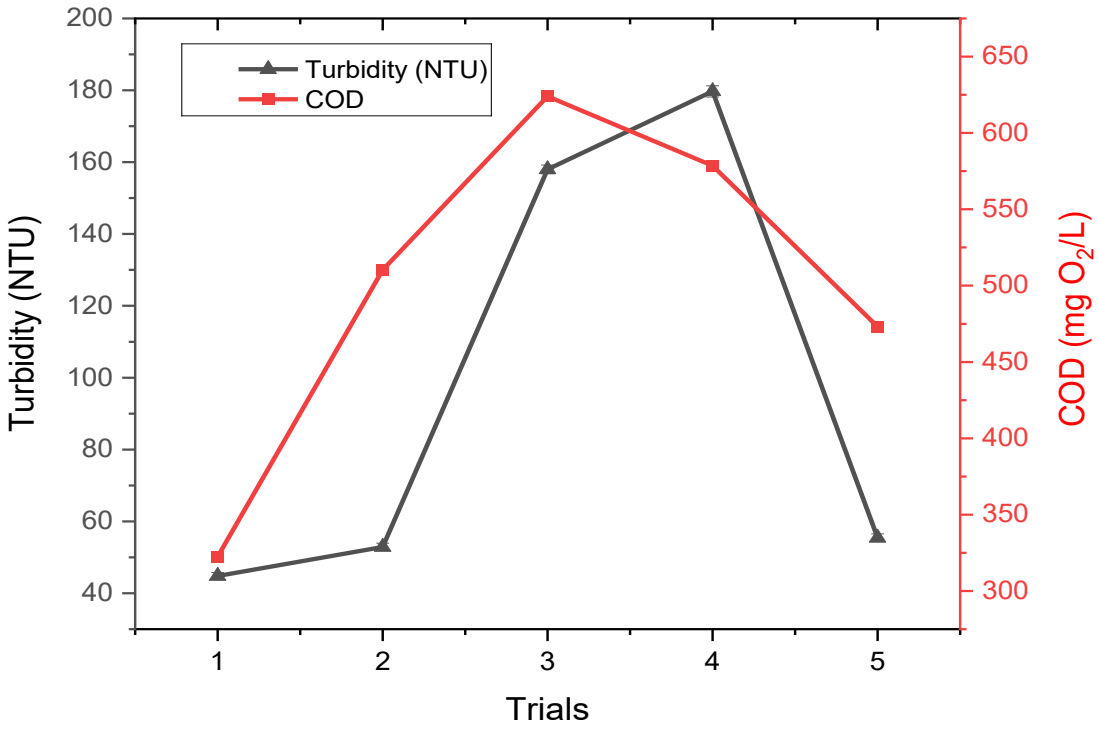


Fig. 9 Evolution of turbidity and chemical oxygen demand (COD) across trials for sample N°1 using cactus gel

The evolution of turbidity and COD over the five trials highlights the complex behavior of suspended solids and organic compounds in textile effluents. Between trials 1 and 3, both parameters increase in parallel, reaching approximately 160 NTU and 630 mg O_2/L, indicating a close correlation between particulate and organic loads, since colloids and suspended matter often act as carriers of organic pollutants. (Munien et al. 2023) However, from trial 3 onwards, a divergence is observed: turbidity continues to rise, while COD decreases, suggesting partial oxidation or biodegradation of soluble compounds, while particles remain in suspension. This behavior supports the fact that coagulation–flocculation primarily targets the removal of suspended solids, whereas the reduction of soluble COD requires complementary processes such as oxidation or biological activity. By trial 5, the simultaneous decrease in turbidity and COD indicates more effective sedimentation, likely promoted by the synergistic action of the chemical coagulant and the cactus-based bioflocculant, whose mucilage is known to enhance floc aggregation and accelerate settling. (Husen et 2024) Overall, these results confirm that turbidity and COD are complementary indicators: the former reflecting mainly the particulate and colloidal fraction, and the latter representing the soluble organic load. (Katheresan et al. 2018) Their simultaneous monitoring therefore appears essential for assessing the effectiveness of textile effluent treatments and guiding the

development of more sustainable processes integrating natural agents such as plant-based bioflocculants. (Husen et 2024; Alazaiza et al. 2025)

The trials were allowed to settle and are presented in the following figure 10:

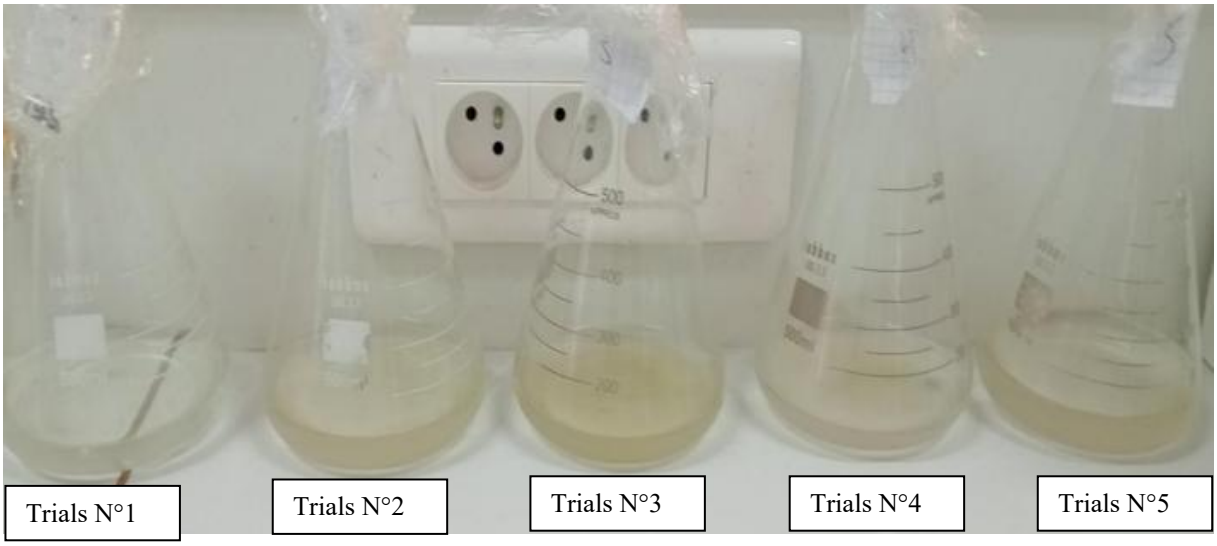


Fig. 10 The results of the treatment tests of Sample N°1 using cactus gel

Cactus gel treatment applied to Sample N°2

The treatment of Sample N°2 with cactus gel highlights its efficiency in reducing pollution from textile effluents (see table 6 and figure 11). The raw wastewater was highly contaminated, with an initial turbidity of 968 NTU and COD of 1200.68 mg O_2/L, confirming its high particulate and organic load. During the five trials, turbidity and COD increased in parallel up to trial 4 (296.2 NTU, 697.83 mg O_2/L), before decreasing sharply in trial 5 (118.42 NTU, 505.3 mg O_2/L). This behavior indicates a strong correlation between suspended matter and organic pollutants, with cactus gel acting more effectively on solid removal than on soluble organic fractions. Conductivity remained relatively stable (11.64–17.94 mS), showing that cactus gel does not alter ionic balance, unlike conventional chemical coagulants. Floc size evolution confirmed the role of cactus mucilage in particle bridging and sedimentation. The best performance was obtained in trial 5, with turbidity removal of 87.8% and COD removal of 57.9%, reflecting an optimal balance of bioflocculant activity (Table 6, Figure 11). Such removal efficiencies are consistent with reported ranges for cactus mucilage in textile wastewater treatment, where turbidity removal commonly reaches 80–90% and COD reductions range between 50 and 70% depending on dosage and conditions. Compared with aluminum salts used in the Sebdou plant, cactus gel provides comparable efficiency without introducing toxic residues. Moreover, the biodegradable sludge generated presents no environmental or health risk, which contrasts with chemical coagulants whose residues and sludge disposal pose ecological concerns. (Bouaouine et al. 2021)These results demonstrate that cactus gel is a sustainable

alternative to conventional treatments, combining efficiency with ecological safety. Its application could contribute to greener wastewater management and circular economy strategies in the textile sector, by reducing chemical usage, minimizing sludge volume, and enabling treatment with a readily available natural resource. This aligns with growing evidence supporting bioflocculants from plants like Opuntia ficus-indica as promising eco-friendly agents for industrial effluent treatment. (Deshmukh and Hedaoo 2018; Das et al. 2021)Thus, the use of cactus gel bioflocculant in textile wastewater treatment presents an effective, environmentally friendly, and economically viable option to conventional chemical coagulation-flocculation processes.

Table 6 The physicochemical analysis results obtained for Sample N°2 following treatment with cactus gel

Trials	Turbidity (NTU)	Conductivity (mS)	COD	Floc size
1	82.93±1.16	11.64±0.92	347.34±1.42	large
2	115.36±1.35	17.31±0.81	515.6±1.95	large
3	223.1±1.37	17.94±0.55	656.7±2.15	medium
4	296.2±1.68	17.27±0.62	697.83±2.10	medium
5	118.42±1.45	17.89±0.73	505.3±1.95	large

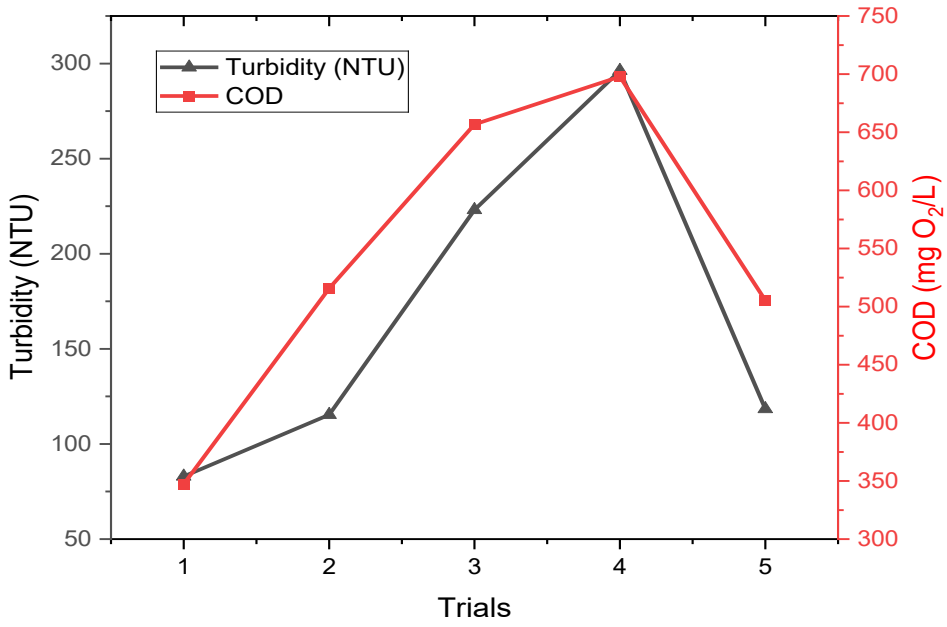


Fig. 11 Evolution of turbidity and chemical oxygen demand (COD) across trials for sample N°2 using cactus gel

Wastewater treatment using cactus powder

The evaluation of sample N°3 textile wastewater treatment by bioflocculation using cactus powder under different saline solution concentrations (0.1 M, 0.7 M, and 1.3 M) highlights the crucial role of ionic strength and treatment mode (control, bioflocculant alone, hybrid) in determining turbidity and COD removal efficiency as presented in table 7 and illustrated in figures 12–14.

The best results were obtained with the control treatment (trial 1), where the conventional chemical coagulants and flocculants used in the Sebdou textile unit were applied. Turbidity dropped to 95.15 NTU, corresponding to a 90.25% removal, and COD to 321.75 mg O_2/L, equivalent to 70.83%. These values confirm the robustness of conventional processes, albeit with the drawback of generating potentially toxic chemical sludge. (Adachi et al. 2023)

In contrast, at 0.1 M, the introduction of cactus bioflocculant (trials 2 and 4) showed more variable performances: turbidity remained high (201.82–502.39 NTU), corresponding to removal efficiencies between 79.32% and 48.62%, while COD was reduced only by 50.28% to 42.3%. These results suggest limited efficiency of cactus mucilage under low salinity, likely due to suboptimal dosing or colloidal instability that favors particle restabilization. (Othmani et al. 2020)

At intermediate salinity (0.7 M), system performance improved markedly. The hybrid treatment (trial 3) combining chemical coagulant, bioflocculant, and chemical flocculant reduced turbidity to 106 NTU (89.13% removal) and COD to 428.8 mg O_2/L (61.15% reduction). The formation of large flocs confirmed the synergistic effect between electrostatic neutralization induced by salts and coagulant, and polysaccharide bridging by cactus mucilage. This synergy aligns with findings from bioflocculant studies showing enhanced efficiency when combined with chemical coagulants. (Choumane et al. 2017)This result identifies 0.7 M as the optimal condition to maximize turbidity removal, achieving efficiency close to chemical control while reducing reliance on synthetic reagents. However, COD removal remained lower than that of the control (70.83% at 0.1 M), indicating that the soluble organic fraction is less affected by the bioflocculant compared to the conventional chemical process. (Othmani et al. 2020)

At high salinity (1.3 M), bioflocculant efficiency decreased. The best result was observed in trial 3, with turbidity reduced to 266.13 NTU (72.73%) and COD to 497.34 mg O_2/L (54.91%). Nonetheless, subsequent trials showed performance decline (up to 546.7 NTU and 675.81 mg O_2/L), suggesting colloidal

restabilization induced by ionic saturation. Although large flocs were formed, their cohesion and settleability appeared compromised, limiting treatment efficiency a phenomenon reported in ionic-strength-dependent bioflocculant activity studies. (Bouaouine et al. 2021)

A cross-comparison of the concentrations highlights that:

- Chemical control (0.1 M, trial 1) achieved the best COD removal (70.83%), but generated non-biodegradable sludge.
- The hybrid treatment at 0.7 M (trial 3) provided the best turbidity removal (89.13%), with acceptable COD reduction (61.15%).
- At 1.3 M, removal efficiencies were lower (72.73% for turbidity, 54.91% for COD) and unstable.

These findings confirm that cactus powder, either alone or in combination with chemical agents, represents a promising alternative to conventional treatments. Its efficiency, however, is strongly conditioned by salinity and treatment mode. At intermediate salinity, the bioflocculant chemical hybrid approach maximizes suspended solids removal while reducing environmental impact, supporting sustainable wastewater management strategies. (Choumane et al. 2017)

Table 7 The physicochemical analysis results obtained for Sample N°3 following treatment with cactus powder

Salt Solution Concentration	Trial	Conductivity (mS)	Turbidity (NTU)	COD (mg O_2 L^{-1})	Floc Size
0.1 M	1	11.97	95.15	321.75	Large
	2	11.32	201.82	548.41	Medium
	3	14.23	193.72	444.84	Large
	4	11.72	502.39	636.43	Medium
	5	15.23	458.48	605.77	Large
0.7 M	1	11.97	95.15	321.5	Large
	2	19.16	280.5	498.0	Medium
	3	17.77	106.0	428.8	Large
	4	18.10	309.4	571.8	Medium
	5	18.71	398.6	581.8	Large
1.3 M	1	11.97	95.15	321,75	Large
	2	22	298.72	552.16	Medium
	3	23.33	266.13	497.34	Large
	4	25.1	546.70	675.81	Medium
	5	23.7	442.57	630.81	Large

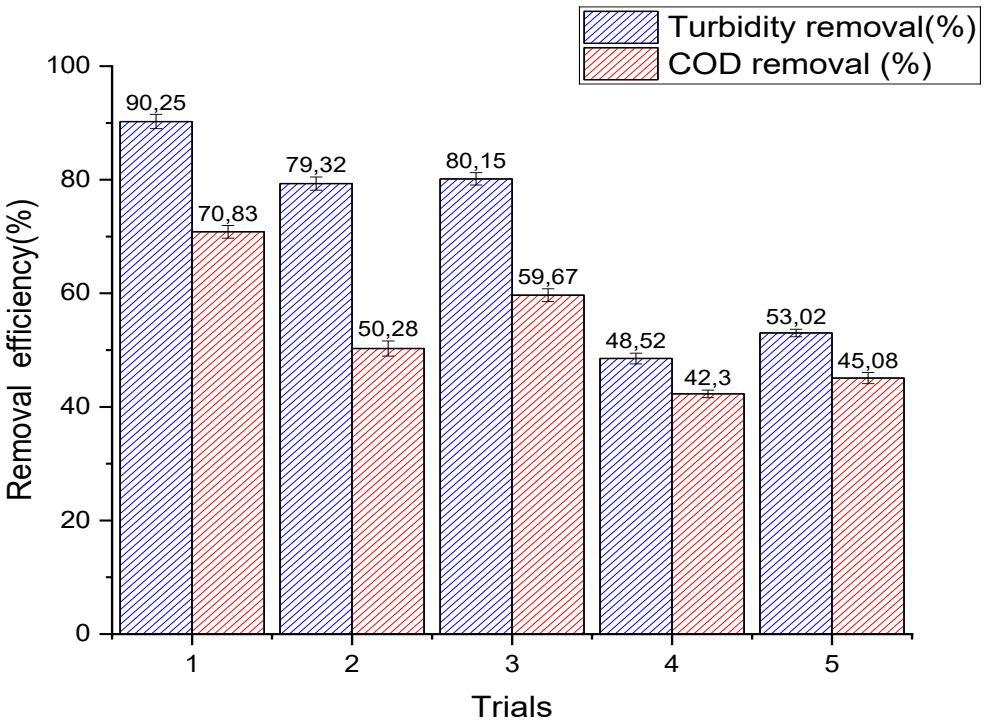


Fig. 12 Comparative removal efficiency of turbidity and cod for wastewater treated with cactus-based bioflocculants powder at salt concentration of 0.7M (sample N°3)

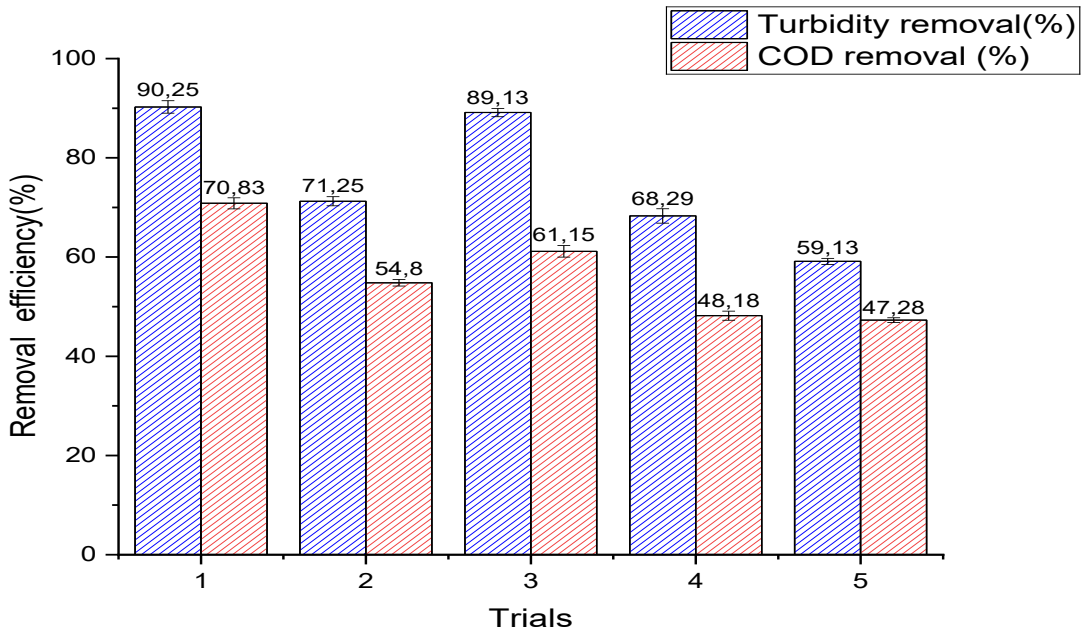


Fig. 13 Comparative removal efficiency of turbidity and cod for wastewater treated with cactus-based bioflocculants powder at salt concentration of 0.7M (sample N°3)

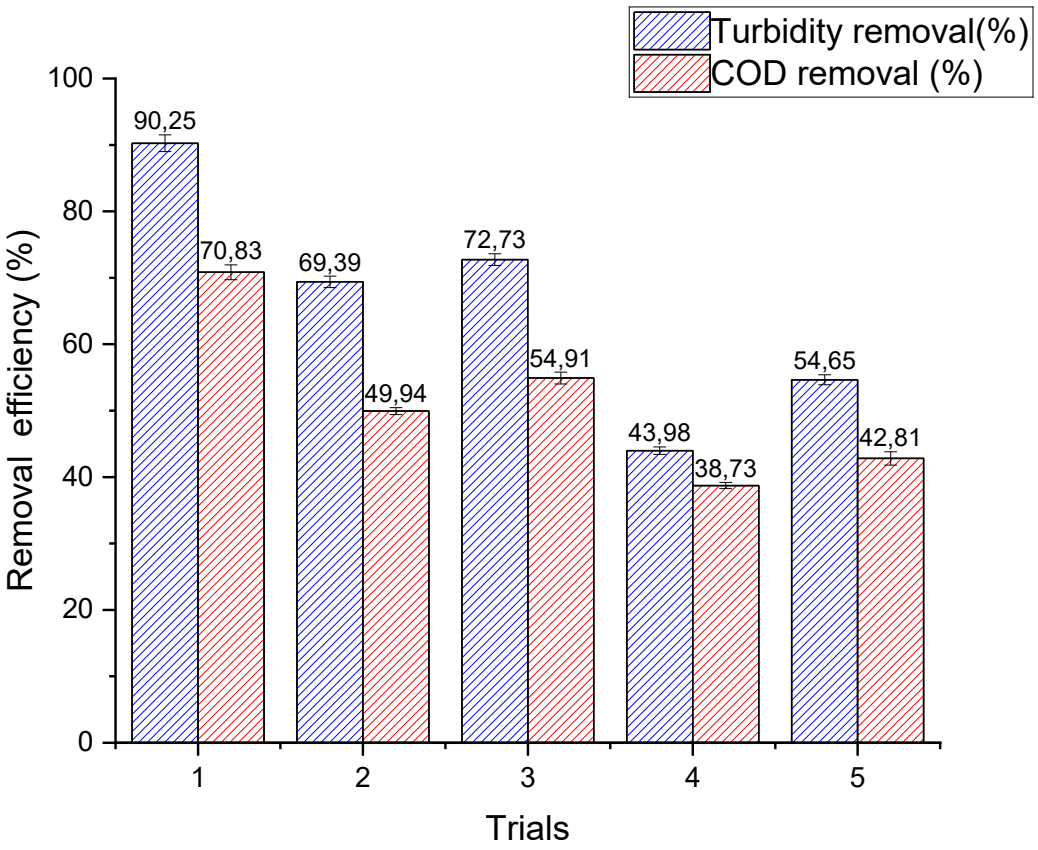


Fig. 14 Comparative removal efficiency of turbidity and cod for wastewater treated with cactus-based bioflocculants powder at salt concentration of 1.3M (sample N°3)

Wastewater treatment using spinach powder

In this part of the study, wastewater from sample N°3 was treated with spinach-based bioflocculants under three saline conditions (0.1, 0.7, and 1.3 M). Five trials were conducted for each salinity level according to the protocols in table 4, and the physicochemical outcomes are summarized in table 8 and illustrated in figures 15–17. The results clearly highlight the role of ionic strength and treatment mode (control, bioflocculant alone, hybrid) in determining removal efficiencies of turbidity and COD. At 0.1 M, the chemical control (Trial 1) delivered the strongest performance: turbidity reduced to 95.15 NTU (90.25% removal) and COD to 321.75 mg O_2/L (70.83%). This confirms the robustness of conventional coagulant–flocculant protocols, though they raise environmental concerns due to the generation of non-biodegradable and potentially toxic sludge. In contrast, spinach-based bioflocculant applications (Trials 2 and 4) were notably less effective: turbidity ranged between 198.71 and 369.86 NTU (79.61–62.12% removal), while COD reduction was limited to 54.92–39.32%. Hybrid treatments (Trials 3 and 5) yielded intermediate results up to 81.07% turbidity removal and about 57.12% COD reduction suggesting a partial

synergy between chemical agents and natural flocculants at low salinity. This limited efficiency at low ionic strength is consistent with the literature: bioflocculants often require sufficient ionic shielding for effective bridging and particle aggregation. (Maćczak et al. 2020)

At 0.7 M, removal efficiencies improved. The hybrid treatment (Trial 3**)** achieved 88.36% turbidity removal and 62.94% COD reduction, supported by the formation of large, stable flocs. This suggests electrostatic neutralization (from salt and coagulant) intensifies the bridging ability of spinach polysaccharides. Similar synergistic effects of combining ions and biopolymer flocculants have been observed in other studies.[53] (Mohammed and Swalaha 2025)

At 1.3 M, the system reached optimum performance. The hybrid treatment (Trial 3) resulted in 91.18% turbidity removal and 66.34% COD reduction the highest values achieved in all spinach-based protocols. Large, cohesive flocs were observed, confirming synergy between ionic strength and biopolymer bridging. However, Trials 4 and 5 exhibited diminished efficiency (down to 72.26% turbidity and 51.34% COD). This drop is likely due to ionic oversaturation, which can destabilize floc cohesion and impair sedimentation a phenomenon reported in ionic-strength-dependent flocculation studies. (Bahniuk et al. 2022)

A cross-comparison of all conditions (table 8; figures. 15–17) highlights three key findings:

1. The chemical control (0.1 M, Trial 1) provided the best COD removal (70.83%) but relies entirely on synthetic reagents and generates non-biodegradable sludge.
2. The spinach-based hybrid treatment at 1.3 M (Trial 3) achieved the best overall performance, with 91.18% turbidity and 66.34% COD removal, confirming it as the optimal condition for maximizing treatment efficiency while reducing reliance on chemical additives.
3. The 0.7 M hybrid system remains a promising intermediate option, with high turbidity removal (88.36%) and acceptable COD reduction (62.94%), but below the 1.3 M peak.

Overall, these findings confirm that spinach powder, used as a bioflocculant alone or in hybrid mode, represents a sustainable alternative to conventional textile wastewater treatments. Its performance is highly dependent on salinity, with 1.3 M emerging as the optimal ionic strength for maximizing suspended solids removal while maintaining a significant reduction of COD.

Table 8 The physicochemical analysis results obtained for Sample No. 3 following treatment with spinach powder

Salt Solution Concentration	Trial	Conductivity (mS)	Turbidity (NTU)	COD (mg O_2 L^{-1})	Floc Size
0.1 M	1	13.00	95.15	321.75	Large
	2	11.52	198.71	497.06	Medium
	3	13.22	184.92	473.24	Large
	4	12.94	369.86	669.82	Medium
	5	13.31	270.77	537.00	Large
0.7 M	1	11.64	95.15	321.75	Large
	2	17.31	216.11	481.17	Medium
	3	17.94	113.73	408.55	Large
	4	17.27	378.50	655.88	Medium
	5	17.89	367.35	598.98	Large
1.3 M	1	14.26	95.15	321.75	Large
	2	25.50	250.95	526.81	Medium
	3	22.80	86.11	371.28	Large
	4	26.70	139.74	524.93	Medium
	5	24.60	110.28	480.20	Large

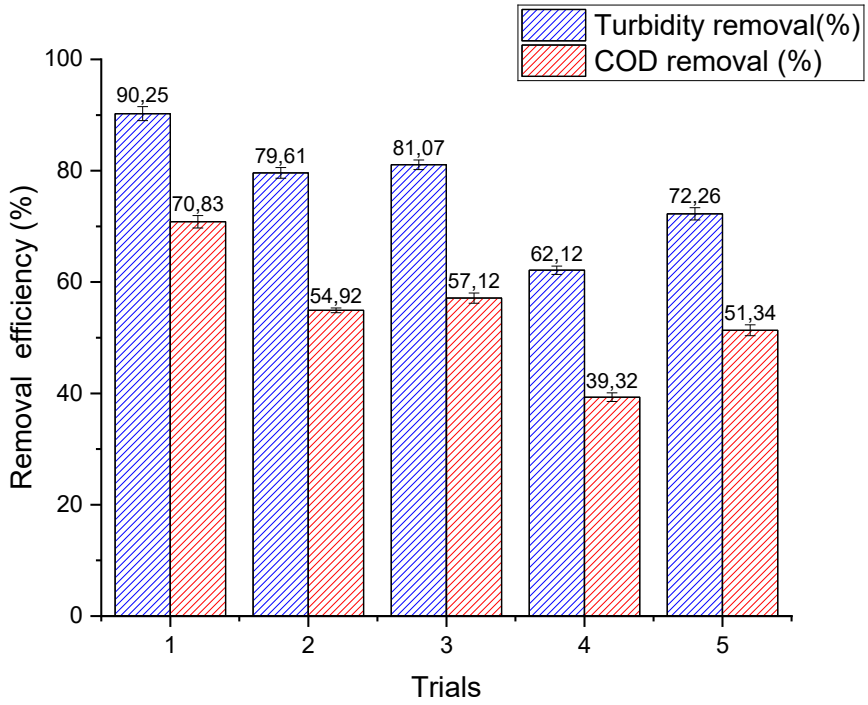


Fig. 15 Comparative removal efficiency of turbidity and cod for wastewater treated with spinach-based bioflocculants powder at salt concentration of 0.1M (sample N°3)

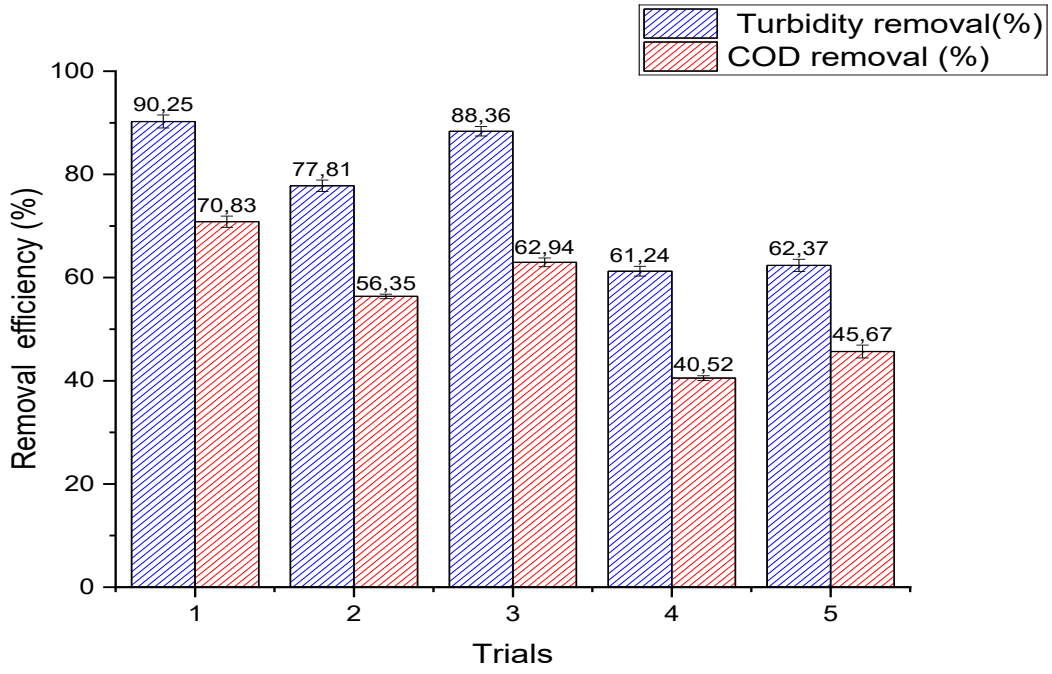


Fig. 16 Comparative removal efficiency of turbidity and cod for wastewater treated with spinach-based bioflocculants powder at salt concentration of 0.7M (sample N°3)

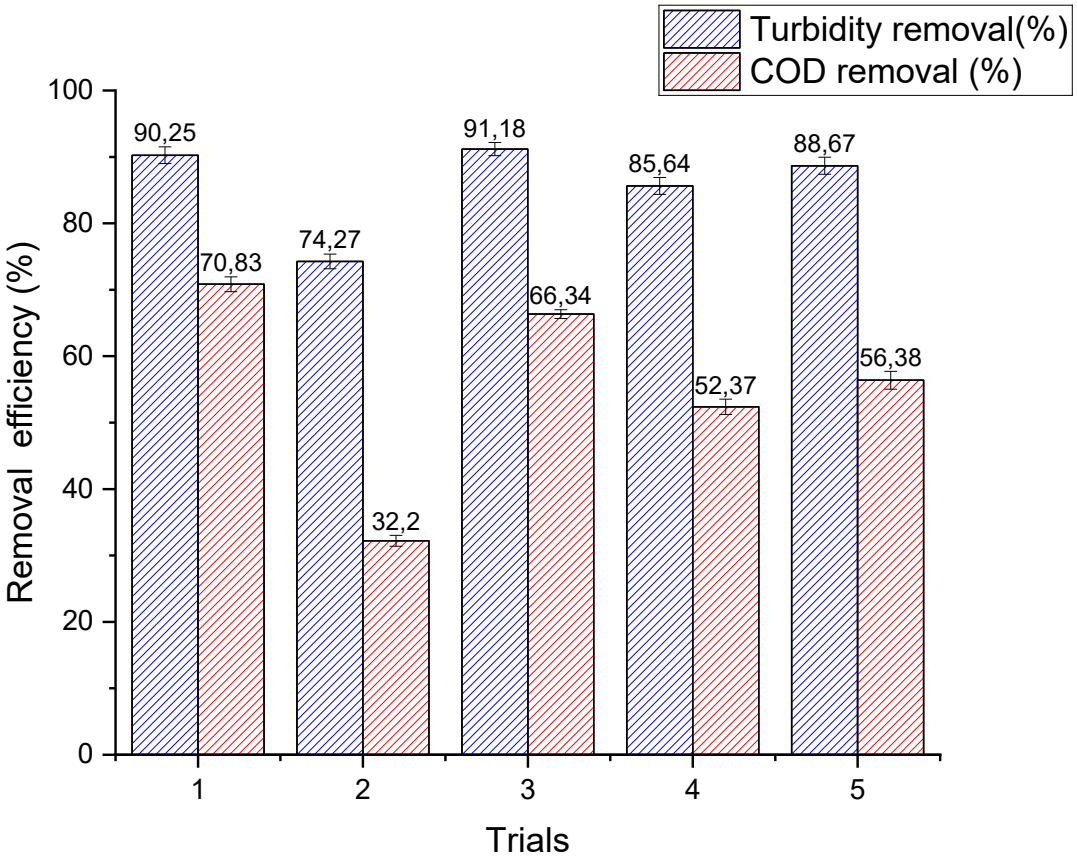


Fig. 17 Comparative removal efficiency of turbidity and cod for wastewater treated with spinach-based bioflocculants powder at salt concentration of 1.3M (sample N°3)

Conclusion

This study successfully demonstrated the potential of plant-based bioflocculants, particularly cactus gel (*Opuntia ficus-indica*) and spinach powder (*Spinacia oleracea*), as eco-friendly and efficient alternatives to conventional chemical coagulants for the treatment of textile industrial effluents. Experiments conducted on real wastewater samples from the Sebdou textile industry revealed that these bioflocculants, whether applied alone or in combination with chemical coagulants, achieved significant reductions in turbidity (up to more than 90%) and chemical oxygen demand (COD), with maximum efficiencies of 66.34%, under optimal experimental conditions. The results also highlight the importance of optimal dosage and saline concentration in maximizing the performance of these natural agents, showing that overdosing or ionic saturation conditions may decrease their effectiveness due to colloidal instability. Moreover, unlike conventional chemical coagulants, the tested bioflocculants preserved the ionic balance of the treated medium and generated biodegradable sludge, which poses far fewer environmental and health concerns. This research supports the integration of cactus- and spinach-based bioflocculants into sustainable

strategies for textile wastewater management, thereby fostering a circular economy by reducing the use of toxic chemical substances, minimizing sludge production, and valorizing locally available natural resources. These findings are consistent with emerging scientific evidence that plant-derived bioflocculants represent a promising pathway to reconcile technical performance, reduced environmental impact, and economic viability in the industrial sector.

Ultimately, the findings of this study reinforce the growing consensus that bioflocculants hold the potential to transform wastewater management practices, opening new avenues for innovation at the intersection of environmental protection, resource valorization, and sustainable industrial development.

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Statements and Declarations

Competing Interests

The authors declare that they have no competing interests.

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