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Research paper

Enhanced coagulation-flocculation of domestic wastewater using sustainable plant-based material: a comparative study of nopal, agave, and eucalyptus

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This study addresses the critical challenge of sustainable wastewater treatment by investigating and valorizing agro-industrial residues as high-performance, zero-waste coagulants. The scope of this engineering investigation was the optimization and comparative assessment of 4 readily available materials – bentonite (BN), eucalyptus leaf powder (ELP), agave powder (AP), and the novel nopal fibrous residue powder (NFRP) – as alternatives to aluminium sulphate (AS) for urban wastewater treatment. The core novelty and innovation lie in the successful utilization of the discarded fibrous residue of the nopal cactus; this approach fundamentally shifts the paradigm from complex, resource-intensive extraction of nopal mucilage to the direct, simple use of a high-volume waste product. This leverages the lignin- and tannin-rich components, which are shown to be responsible for bio-flocculation, making the process intrinsically simpler, cheaper, and scalable, relative to state-of-the-art mucilage-based technologies. The statistical analysis confirmed significant differences in pollutant removal based on the material ($p < 0.01$). Agave powder (AP) was statistically superior for clarity, achieving a maximum turbidity removal percentage (TRP) of 97.76 ± 2.180% at an optimal dose of 20 mg/L, statistically outperforming AS. Conversely, for the removal of organic pollutants, the chemical standard AS was superior in single-dose trials, with COD reduction (CODR) ≈ 88.5%. However, the synergistic combination of NFRP (100 mg/L) and BN (60 mg/L) achieved the highest CODR ≈ 92.13 ± 0.398%, successfully exceeding the performance of AS. Furthermore, AP demonstrated high effectiveness in ammoniacal nitrogen removal (≈ 75%), highlighting its multi-pollutant capacity.

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INTRODUCTION

Water scarcity is a critical global issue, exacerbated by rapid industrialization and urbanization, which have led to increased pollution of water sources (Mitiku, 2020; Nimesha et al., 2022). This growing problem poses significant risks to human health and economic development, particularly in developing countries where contaminated water is a major cause of waterborne diseases. Consequently, there's a pressing need for cost-effective and environmentally friendly methods for water protection and remediation (Mitiku, 2020). In response to this, the reclamation of domestic and industrial wastewater has become a primary solution (Meftah et al., 2023). Various technologies, including ion exchange, membrane filtration, activated carbon, and coagulation/flocculation, are employed for removing contaminants from wastewater (Das et al., 2021). These methods aim for cost-effectiveness, short processing times, and minimal environmental impact. Coagulation is a widely used water treatment technique that adds a coagulant to destabilize and aggregate these suspended particles, forming larger clusters that can be easily separated by sedimentation or filtration (Iwuozor et al., 2023). The coagulation consists of a rapid chemical phase, where coagulants like aluminium sulphate or ferric chloride are added to destabilize colloidal suspensions by neutralizing their electrical charges, followed by flocculation, a slow physical stage where synthetic anionic or cationic polymers are introduced to facilitate the aggregation of these destabilized particles into larger clusters called flocs. These flocs settle by gravity, allowing for the clear separation of treated water from the sediment (Ihaddad et al., 2022).

Historically, chemical coagulants and flocculants, such as aluminium salts (e.g., aluminium sulphate) and iron salts, along with synthetic organic polymers like polyacrylamide, have been extensively used (El Mouhri et al., 2024). Despite their high efficiency, these conventional coagulants have significant drawbacks. Excessive aluminium residuals have been associated with neurotoxicity and serious health issues like Alzheimer's disease (El-taweel et al., 2023; Mitiku, 2020; Arris et al., 2021), and other potential risks including neurotoxic effects, excessive fragility, severe encephalopathy in renal dialysis patients, and bone softening leading to osteomalacia (Krupińska, 2020). Research across regions confirms the presence of aluminium in water samples, often related to the use of aluminium sulphate in water treatment processes, underscoring the necessity of monitoring residual aluminium levels as influenced by water treatment (Weisner et al., 2023).

Synthetic polymers may also contain traces of toxic and carcinogenic acrylamide monomers (Das et al., 2021). However, the standard use of synthetic coagulants like polyaluminium chloride (PACl) carries significant drawbacks, including residual toxicity, environmental persistence, high operational costs, and health risks associated with excessive aluminium levels (Diver et al., 2023). Therefore, there is a growing imperative to explore sustainable and eco-friendly alternatives, such as plant-derived natural coagulants (Agarwal and Saini, 2022). Leveraging locally sourced plant materials can mitigate the ecological and health risks associated with synthetic chemicals, reduce lifecycle impacts, lower carbon footprints, and promote a more sustainable and circular water treatment approach (Agarwal et al., 2024; Ugural et al., 2024).

Among these, plant-based coagulants are particularly promising, with biopolymers extracted from various plant parts like leaves, seeds, and mucilage, containing active compounds such as polysaccharides, polyphenolic compounds, and proteins (El-taweel et al., 2023; Kumar et al., 2024; Kurniawan et al., 2023). These compounds facilitate polymer bridging or charge neutralization, leading to the formation of easily separable flocs (Kumar et al., 2024). Examples include the well-known *Moringa oleifera* seeds, cactus mucilage (Trindade et al., 2021; Shoukat et al., 2023; Fernández-Martínez et al., 2024), and various other plants like *Manihot esculenta* and *Syzygium polyanthum* (Kurniawan et al., 2023; Da Silva et al., 2025). The shift towards plant-based coagulants aligns with the global movement towards sustainable and cost-effective solutions for water and wastewater treatment (Yolanda et al., 2022; Kumar et al., 2024). The green coagulation-flocculation process using natural coagulants also offers the potential for recycling primary treatment sludge as fertilizer, aligning with Sustainable Development Goal (SDG) 6 (Hussain and Al-Baldawi, 2025).

Plants such as eucalyptus and pine are rich sources of tannins, which are water-soluble, non-toxic polyphenols found in various plant parts, including leaves, bark, and roots, which can bind and precipitate organic compounds (Thelmmer et al., 2024). The use of tannins derived from plants as a sustainable and healthier option compared to aluminium-based coagulants has been explored (Tomasi et al., 2023). Other studies have also shown the effectiveness of biocoagulants derived from plants like moringa, chickpea, *Aloe vera* and avocado seeds in reducing water turbidity without causing secondary contamination (Tsamo et al., 2021).

Bentonite has been tested as a high-surface-area mineral coagulant, and eucalyptus leaf powder, rich in polyphenolic tannins, and agave powder, containing complex biopolymers, have been tested as natural coagulants. The core novelty and research gap addressed by this study is the utilization of the discarded fibrous residue of the nopal cactus as a direct-use, high-performance flocculant. This approach fundamentally shifts the paradigm from complex mucilage extraction to the simple valorization of a high-volume agro-industrial waste product. The rationale for proposing this particular method is that the nopal fibrous residue is rich in structural biopolymers like lignin and cellulose fibres, whose structural groups and polymer chains are hypothesized to facilitate superior and selective pollutant binding and flocculation, directly integrating structure and performance-improving mechanisms.

MATERIAL AND METHODS

Sample collection and characterization

The domestic wastewater used in our study (Table 1) was collected from the Ain El Houtz Wastewater Treatment Plant (WWTP) located in Tlemcen, Algeria. The samples were taken at the outlet of the sand and oil removal process (after the pre-treatment).

Jar test

The coagulation was done using a jar test. The coagulation phase consists of rapid agitation at 200 r/min for 3 min, after which the stirring speed is reduced to 40 r/min for a further 20 min of slow agitation. Upon completion of the stirring phase, the agitation is ceased, and the solution decanted after 15 min. The supernatant from each beaker is carefully collected, and its turbidity, pH, and conductivity are measured. From these measurements, the optimal coagulant dose is determined according to the lowest turbidity removal percentage.

In this study, we tested aluminium sulphate (Al_2SO_4), bentonite, eucalyptus leaf, and agave plant as coagulants, and nopal fibrous residue powder (NFRP) as flocculant.

The parameters tested in the study were: turbidity measured by HANNA HI 9370, pH measured by WTW pH 3110, conductivity (EC) measured by HANNA HI 8633, COD measured by oxidation with potassium dichromate method, ammoniacal nitrogen measured by the titration method. The supernatant is withdrawn for analyses after 30 min of settling. The turbidity removal percentage (TRP), ammoniacal nitrogen removal (TANR) and COD removal (CODR) were determined to investigate the efficacy of the tested coagulants.

The measurement of COD and ammoniacal nitrogen only took place for the optimal dose after the coagulation-flocculation phase ($COD_{optimal}$ and $TAN_{optimal}$).

Preparation of aluminium sulphate (AS), bentonite (BN) solution

The aluminium sulphate (Al_2SO_4) (FULKA), and bentonite (from ENOF factory in Maghnia-Algeria) solutions were prepared by introducing 1 g of each (separately) to 1 L of distilled water under magnetic stirring, after which the solutions were stored in a glass jar. The concentration of the solution was therefore 1 g/L. The addition of increasing doses during coagulation/flocculation is performed using the prepared solution.

To facilitate interpretation of the results, the doses that have been added during the experiments were converted to concentrations for presentation in the tables in the results section.

Preparation of nopal solution

The prickly pear cactus (also know as nopal) used in the study comes from the wilaya of Sidi Bel Abbes, Algeria. The cladodes were thoroughly washed, and the spines were removed using scissors and tweezers. The cactus cladodes (paddles) were air-dried for 2 days, then cut into 2 cm cubes (Fig. 1) and ground with a Thomson brand food processor, adding distilled water (volume of added water was 1.5 L). The aqueous plant extract was collected and then filtered using stockings. The retrained solids in the stocking, that we named the 'nopal fibrous residue' (NFR), were retrieved and placed in an oven at 80°C for 72 h. After drying, the NFR was ground with a Thomson brand food processor and then sieved, resulting in a collected powder of 0.2 mm.

Table 1. Wastewater parameters

Parameter	Range	Average	Standard deviation
pH	7.5–8	7.75	0.14
Conductivity (µS/cm)	900–1 335	1 117.5	125.57
Turbidity (NTU)	70–95	82.5	7.21
COD (mg/L)	190–500	345	89.48
Ammoniacal nitrogen (mg/L)	60–80	70	5.77

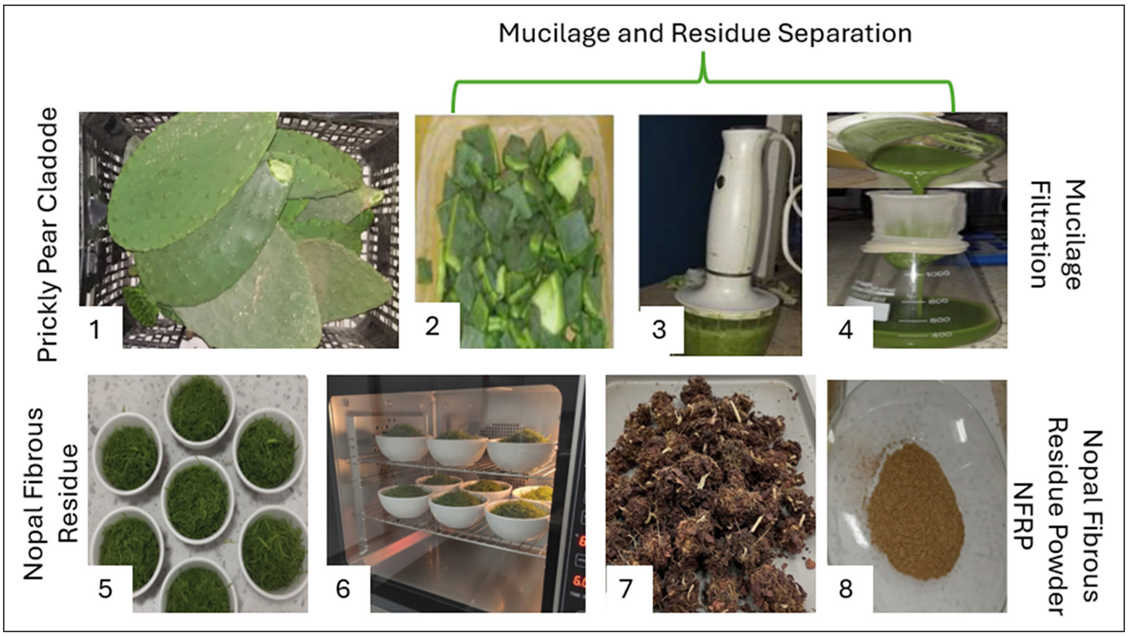

Figure 1. Preparation of the nopal fibrous residue powder: (1) prickly pear cladode; (2) cut cladodes; (3) grinding cut cladodes; (4) filtering the juice with a stocking; (5) retrieving the retained nopal residue; (6) oven drying the nopal residue; (7) dried nopal residue; (8) nopal fibrous residue powder

Figure 2. Preparation of eucalyptus leaf powder and agave powder: (1) plant harvesting (2) oven drying (3) dried plants (4) grinding

The nopal fibrous residue powder (NFRP) solution was then prepared by mixing 2 g of NFRP with 1 L of distilled water in a beaker. The mixture was then magnetically stirred for 30 min, and filtered using a filter paper (MN 616 md, Ø 125 mm, Nr. 2, REF 433 012, Macherey-Nagel (MN) brand, pore diameter 4 to 12 µm) filtration setup. The filtrate was collected and stored in a glass jar, representing the solution to be used as a flocculant. The concentration used in the experiments ranged between 16 to 200 mg/L.

Preparation of eucalyptus leaf and agave solutions

The eucalyptus leaf (*Eucalyptus radiata*) and agave plant (*Agave americana*) used in the study came from the wilaya of Tlemcen, Algeria (Fig. 2). The eucalyptus leaves and agave were thoroughly washed, then dried in an oven at 105°C and 60–90°C, respectively, for 72 h. After drying, the leaves and the plant were ground with a Thomson brand food processor and then sieved, resulting in a collected powder of 0.2 mm. The eucalyptus leaf powder (ELP) and agave powder (AP) solutions were prepared by mixing 1 gram of the obtained powder with 1 L of distilled water in a beaker (separately); then the mixture was magnetically stirred for 30 min, and filtered using a filter paper filtration setup (MN 616 md, Ø 125 mm, Nr. 2, REF 433 012, Macherey-Nagel (MN) brand, pore diameter 4 to 12 µm). The filtrate was collected and stored in a glass jar, representing the solution to be used.

Statistical analysis

To validate the findings and rigorously compare the performance of the four coagulant groups (the chemical standard, AS, and the natural alternatives, AP, ELP, and BN), a comprehensive 1-way analysis of variance (ANOVA) was performed separately for both the turbidity removal percentage (TRP) and the COD removal percentage (CODR). The objective was to determine if statistically significant differences existed among the mean removal efficiencies at a significance level of $\alpha = 0.05$. Prior to the ANOVA, the assumption of homogeneity of variances across the groups was assessed using Levene's test. Where the ANOVA yielded a statistically significant result ($p < 0.05$), a Tukey's honestly significant difference (HSD) post-hoc test was subsequently applied. This post-hoc analysis was crucial for identifying the specific pairs of coagulants that exhibited statistically different mean performances, thereby establishing a clear, ranked order of effectiveness for both TRP and CODR.

RESULTS

The coagulation-flocculation treatment process was tested for urban wastewater using 3 natural coagulants (eucalyptus leaf, bentonite, and agave plant), one chemical coagulant (aluminium sulphate) and one natural flocculant (nopal fibrous residue). For each coagulant/flocculant concentrations were varied in order to find the optimal doses. Different trials were performed to confirm the efficiency of the coagulants and flocculants and also to validate the results (see Tables A1–A7, Appendix). Table 2 represents the standard deviation for the trials for each coagulant and flocculant.

For the coagulation phase (Fig. 3), the aluminium sulphate optimal dosage was found to be the highest, at 150 mg/L, followed by that for eucalyptus, bentonite and agave, at 90 mg/L, 60 mg/L, and 20 mg/L respectively. The highest turbidity removal percentage (Fig. 4) was recorded for agave at 97.76 ± 2.180%, then bentonite, aluminium sulphate and eucalyptus at 93.25 ± 1.692%, 91.63 ± 2.13%, and 88.05 ± 1.852%, respectively.

The highest COD removal percentage was recorded for aluminium sulphate at 88.47 ± 0.775%, then for eucalyptus, bentonite and agave, at 77.71 ± 1.680 %, 75.25 ± 0.929%, and 58.17 ± 2.693%, respectively. The highest ammoniacal nitrogen removal percentage was recorded for agave at 75%, then aluminium sulphate, bentonite and eucalyptus at 50%, 50% and 25%, respectively.

The average pH values recorded for aluminium sulphate, bentonite, eucalyptus, and agave were 8.920 ± 0.128, 8.80 ± 0.079, 8.71 ± 0.076, and 8.07 ± 0.310, respectively. The mean conductivity for these same coagulants reached 1 176 ± 223.63 µS/cm, 981 ± 36.94 µS/cm, 1 032.50 ± 87.28 µS/cm, and 883.50 ± 52.30 µS/cm, respectively.

For the flocculation phase (Fig. 5), different dosages of nopal fibrous residue powder were tested as a flocculant that was separately combined with the optimal doses of aluminium sulphate and bentonite.

The optimal dosage of nopal fibrous residue was found to be 100 mg/L when combined with an aluminium sulphate concentration of 150 mg/L, and which achieved turbidity, COD and ammoniacal nitrogen removal percentages of 96.3 ± 0.386%, 89.42 ± 0.485%, and 79%, respectively (Fig. 4). For pH and conductivity, the averages were 7.78 ± 0.034 and 1 182.0 ± 19.270 µS/cm, respectively.

The optimal dosage of nopal fibrous residue combined with bentonite (60 mg/L) was found to be 100 mg/L, which achieved turbidity, COD and ammoniacal nitrogen removal of 89.35 ± 1.443%, 92.13 ± 0.398%, and 72%, respectively. The water pH remained stable and slightly alkaline, averaging 8.04 ± 0.131, while the conductivity averaged 1 229.38 ± 62.577 µS/cm.

Statistical analysis, using ANOVA and the subsequent Tukey's HSD tests, reveals a significant decoupling of coagulant performance based on the target pollutant, which critically impacts the objective of replacing the chemical standard, aluminium sulphate, with natural alternatives. For turbidity removal percentage (Table 3), the analysis (p = 0.000142) confirms significant differences, with agave powder emerging as the superior choice (mean TRP ≈ 97.8%). Agave powder was found to be significantly better than all other coagulants, including aluminium sulphate (mean TRP ≈ 91.6%), thus confirming its viability as a high-performance natural replacement for maximizing clarity. Conversely, the analysis for COD removal percentage (Table 3) ($p = 9.93 \times 10^{-11}$) showed that the chemical standard AS was significantly superior (mean CODR ≈ 88.5%) to all natural alternatives. The high-performing agave

Table 2. Standard deviation for the tested parameters with the optimal doses of coagulants and flocculant

Coagulant/flocculant (optimal dosage)	Standard deviation					
	pH	Conductivity (µS/cm)	Turbidity (NTU)	TRP (%)	COD (mg/L)	CODR (%)
AS (150 mg/L)	0.128	223.625	1.977	2.13	3.87	0.775
BN (60 mg/L)	0.079	36.941	1.437	1.692	4.646	0.929
ELP (90 mg/L)	0.076	87.279	1.590	1.852	8.430	1.680
AP (20 mg/L)	0.310	52.297	1.849	2.180	13.406	2.693
AS (150 mg/L) + NFRP (100 mg/L)	0.034	19.270	0.296	0.386	2.421	0.485
BN (60 mg/L) + NFRP (100 mg/L)	0.131	62.577	1.043	1.443	1.952	0.398

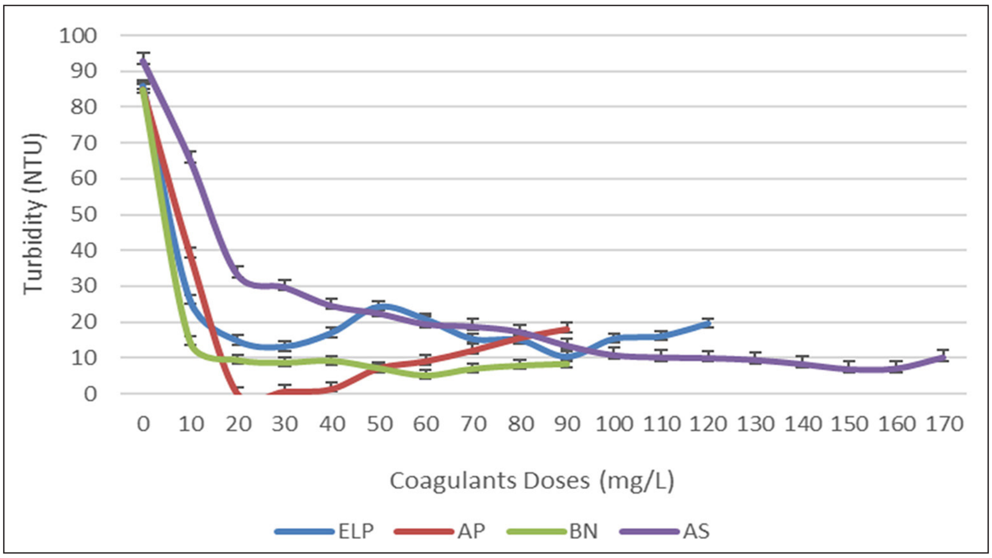

Figure 3. Variation of turbidity with different doses of coagulants (eucalyptus leaf plant, agave plant, bentonite and aluminium sulphate)

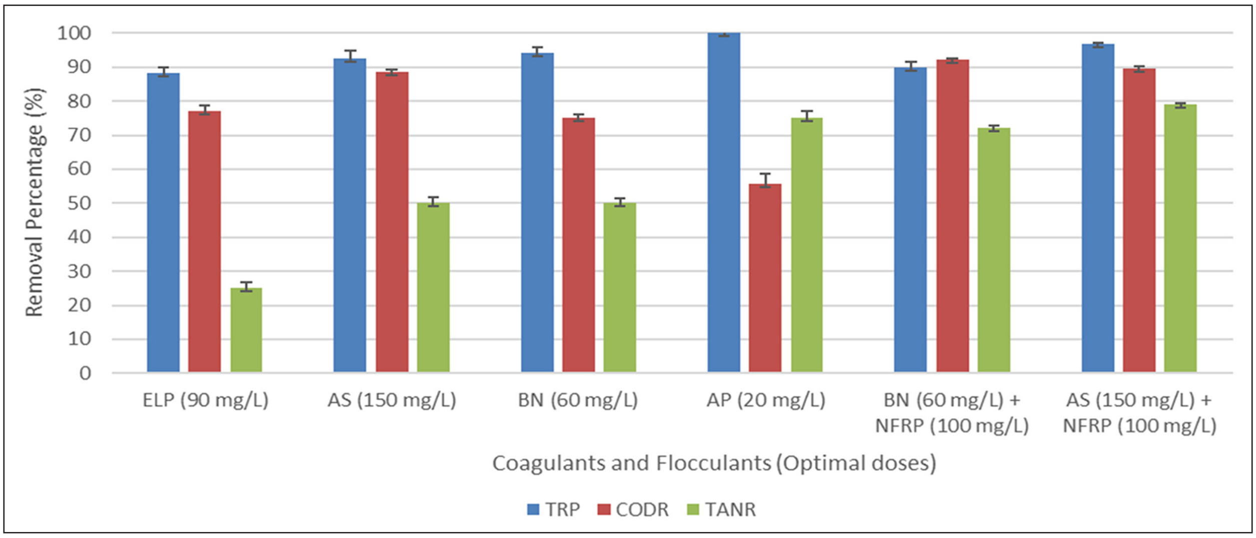

Figure 4. Removal percentage for turbidity, COD and ammonium nitrogen with optimal doses of coagulants and flocculant

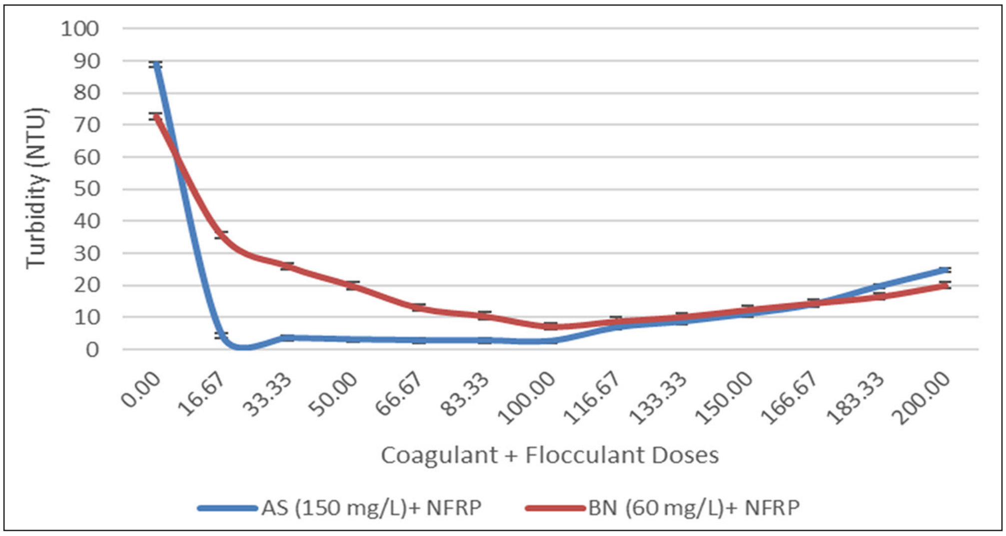

Figure 5. Variation of turbidity with different doses of nopal fibrous residue powder as a flocculant combined with aluminium sulphate and bentonite

Table 3. Statistical analysis of results for turbidity and COD removal percentage

Parameters	Source	Sum of squares	df	*F*-statistic	*p*-value (Pr > F)
Turbidity	Coagulant	194.61	3	16.64	0.000142
	Residual	46.78	12	-	-
COD	Coagulant	1 887.56	3	218.11	9.93×10^{-11}
	Residual	34.62	12	-	-

powder actually yielded the worst CODR (mean ≈ 58.2%), which was found to be significantly worse than all others. This outcome highlights that while agave powder successfully exceeds aluminium sulphate performance for turbidity, the replacement is unsuccessful when targeting high organic matter reduction. The other natural materials, eucalyptus leaf and bentonite, formed a statistically homogeneous middle ground for CODR, suggesting their mechanisms hold better potential for organic removal than agave powder. Ultimately, the search for a universal natural replacement requires prioritizing the most critical treatment objective, as aluminium sulphate remains the best option for COD reduction, while agave powder is the best option for turbidity removal.

DISCUSSION

The stabilization and subsequent removal of pollutants in wastewater treatment are governed by a complex interplay of physical and chemical pathways, primarily involving charge neutralization, electrostatic patching, and interparticle bridging. According to Diver et al. (2023) the coagulation process begins when negatively charged colloidal surfaces are coated by oppositely charged coagulants, reducing the zeta potential toward a net-zero charge and allowing Van der Waals forces to overcome electrostatic repulsion. This can occur through an electrostatic patch mechanism, where cationic species create localized areas of opposite charges on the colloid, drawing particles together. In the case of high-molecular-weight polymeric coagulants, long-chain polyelectrolytes stretch into the solution to form threads that physically bridge the gaps between multiple particles, a process that can lead to gel formation and significantly minimize sludge volume (Ayat et al., 2021). Furthermore, the overall efficiency of the system may result from a combination of mechanisms, including double-layer compression, adsorption, and sweep flocculation or enmeshment within the colloidal floc (Ayat et al., 2021). This is supported by Bouaouine et al. (2021), who observed that biocoagulation specifically facilitates pollutant removal through entrainment and sweeping during the slow settling phase. Collectively, these mechanisms, ranging from the microscopic neutralization of surface charges to the macro-scale physical trapping of particles, define the effectiveness of both chemical and natural treatment agents. Biocoagulants specifically act through the presence of active compounds, and their efficiency is directly associated with their structural characteristics and the presence of functional groups such as hydroxyl (–OH), carboxyl (–COOH), and amino ($–NH_2$). As noted by Da Silva et al. (2025) these groups play key roles in the coagulation stage by helping to neutralize inherent charges and in the flocculation stage by facilitating the formation of bonds between particles. For lignocellulosic biocoagulants, these specific functional groups and their inherent charges favour the coagulation-flocculation process, bridging the gap between molecular chemistry and physical pollutant removal.

The results demonstrated that agave powder (AP) reached the highest turbidity removal at a low dosage. This efficiency can be attributed to its potential sources of phytochemicals such as polyphenolic compounds; Bermúdez-Bazán et al., (2024), Maazoun et al. (2019) and Morreeuw et al. (2021) identified agave as rich in phytochemicals, specifically glycosylated flavonoids like quercetin and kaempferol. These polyphenolic compounds contain hydroxyl (–OH) and carboxyl (–COOH) groups which, as noted by Da Silva et al. (2025), facilitate charge neutralization and interparticle bridging. The mechanism by which agave plant achieves this high efficiency is likely similar to the 'adsorption and bridging' or 'adsorption and charge neutralization' mechanisms identified for other mucilage- and tannin-based coagulants. Kumalasari (2021) stated that *Aloe vera* functions as a biocoagulant because of its complex carbohydrates, sugars, and the active substance 'mucilage', which bind particles in the water. Given the biological similarities between agave and these plants, it is highly probable that AP's effectiveness stems from a similar composition.

The performance of eucalyptus leaf in achieving significant turbidity removal is driven by its high concentration of condensed tannins and phenolic acids, which allow it to serve as a sustainable alternative to synthetic chemicals. As suggested by Tomasi et al. (2023), Hadadi et al. (2022), and Thelmmer et al. (2022), the coagulation mechanism is the adsorption and charge neutralization of the cationic nature of these tannins that allows them to bind with and neutralize the negative charges of suspended particles, leading to flocculation and subsequent removal. This is further corroborated by Dey et al. (2022), who demonstrated the high adsorption capacity of eucalyptus leaves for methylene blue dye, a clear indicator of their ability to bind to and remove pollutants from water.

This mechanism is supported by the FTIR analysis conducted by Lams et al. (2024), which identified a rich composition of phenolic compounds, tannins, and flavonoids characterized by hydroxyl and carbonyl functional groups. These extracts also contained lipids, fatty acids, and quinones that contributed to the overall chemical reactivity of the coagulant. According to Ait Benhamou et al. (2021) and Nuramdhani et al. (2024), eucalyptus leaves contain an essential oil and a diverse array of phenolics, including chlorogenic, gallic, ferulic, and ellagic acids, alongside catechins and flavonoids. The presence of these bioactive compounds underpins the plant's ability to act as an effective agent for coagulation and flocculation, while the polysaccharides and esters found within the plant provided the structural complexity necessary for pollutant binding. As noted by Da Silva et al. (2025) the use of leaves as industrial biocoagulants has gained prominence due to these active functional groups, which aid in contaminant removal while offering the advantages of low cost and wide availability. However, the availability of these specific compounds remains dependent on the plant part and the extraction solvent used during the preparation process.

The superior performance of aluminium sulphate (AS) in COD removal can be attributed to the complex hydrolysis of Al_3^+ ions. As noted by El-taweel et al. (2023), when alum is added to an aqueous solution, it develops massive positively charged complexes and hydroxometal polymers that eventually form aluminium hydroxide precipitates. This process, as described by Zaki et al. (2023) allows the Al^{3+} ions to neutralize the negative charges on colloidal particles, reducing electrostatic repulsion and facilitating coagulation. This chemical 'sweep flocculation' mechanism, highlighted by Ayat et al. (2021), is likely why AS outperformed natural alternatives in removing organic matter (COD), as the gelatinous flocs can trap dissolved organic molecules that smaller natural polymers might miss. However, the high dosage required for AS and the resulting impact on pH and conductivity suggest a need for more sustainable alternatives like bentonite.

Bentonite achieved high turbidity removal at a much lower dose than that reported in other studies; for instance, Zaki et al. (2023) required a 4 times higher dose for similar results. This efficiency is supported by Ahari et al. (2019), who noted that bentonite performance is highly dependent on initial turbidity levels, where the electrostatic attraction between the clay particles and pollutants drives the formation of stable flocs.

The performance of nopal fibrous residue (NFR) as a high-efficiency bio-flocculant is fundamentally linked to its complex lignocellulosic and biochemical composition. As highlighted by Missaoui et al. (2020) and Ait Benhamou et al. (2021) *Opuntia ficus-indica* cladodes are a rich source of structural polysaccharides, including cellulose (21.6 wt%), hemicellulose, and lignin, which constitute the fibrous backbone of the plant. These fibres, characterized by a hierarchical structure spanning from the metric to the nanometric scale, provide a robust physical matrix for pollutant entrapment. According to Sánchez-Moreno et al., (2025) such plant fibres serve as highly effective adsorbents, a property further enhanced in NFR by the presence of functional groups. FTIR observations by Jamhoura and Al-Msiedeen (2025), as well as Ihaddad et al. (2022), confirm the presence of hydroxyl (–OH), carboxylate ($-COO^-$) and amine ($–NH_2$) groups within the fibrous structure. These functional groups are essential for the bio-flocculation process, as they facilitate the formation of hydrogen bonds and electrostatic interactions between the biomaterial and suspended particles.

The mechanism by which NFR promotes flocculation is primarily driven by adsorption and interparticle bridging. Unlike smaller chemical coagulants, the long-chain biopolymers found in nopal fibres, specifically galacturonic acid and pectin, stretch into the wastewater to bridge the gaps between numerous colloidal particles. As noted by Ayat et al. (2021) and Sbai et al. (2024), this biopolymeric structure provides a vast array of unoccupied adsorption sites, leading to the formation of large, stable flocs and a significant reduction in sludge volume. Meftah et al. (2023) further suggest a synergistic effect where quercetin and starch within the plant material enhance this bridging power. Interestingly, Bouaouine et al. (2021) provide evidence that the flocculant properties of OFI are strongly linked to water-soluble biomolecules like phenols and tannins originating specifically from the fibrous, structural parts of the plant rather than the mucilage alone.

Furthermore, the presence of proteins within the nopal structure contributes to its coagulative ability. Ali et al. (2019) and Jamhour and Al-Msiedeen (2025) highlight that these proteins can act as cationic polyelectrolytes, destabilizing and neutralizing negatively charged turbid particles upon contact. This dual action of charge neutralization by proteins and physical bridging by lignocellulosic fibres allows NFR to effectively remove COD, turbidity, and nitrogen. The importance of the fibrous residue is comparable to other abundant agro-wastes, such as sugarcane bagasse, which Iwuozor et al. (2023) identify as a potent precursor for bio-coagulants due to its rich lignocellulosic content. Ultimately, the efficiency of NFR is dependent on proper preparation; as Kurniawan et al. (2023) emphasize, specific drying and grinding processes are required to ensure that the active fibrous compounds and proteins are preserved and their surface area is maximized for optimal contact with the wastewater pollutants.

LIMITATIONS

Despite the promising performance of the natural coagulants tested, this study is subject to several constraints that must be considered when interpreting the results. First, the research was conducted at a laboratory scale using standard jar-test protocols, which may not fully replicate the complex hydraulic conditions and continuous flow dynamics of industrial treatment plants. Second, the evaluation relied on a single wastewater source; as such, the findings do not account for the temporal and seasonal variability of urban effluents, which can significantly alter the chemical matrix and pollutant load. Furthermore, this study lacked a formal cost-benefit analysis and long-term operational assessment, leaving the economic feasibility of large-scale processing and storage of these agro-wastes compared to aluminium sulphate (AS) yet to be determined. Finally, while removal efficiencies were recorded, the study did not include a detailed toxicity assessment of the treated water or a comprehensive characterization of the resulting sludge

CONCLUSION

This study successfully demonstrated the viability of 4 locally sourced natural materials – bentonite (BN), eucalyptus leaf powder (ELP), agave powder (AP), and nopal fibrous residue powder (NFRP) – as high-performance alternatives to the standard chemical coagulant, aluminium sulphate (AS), for urban wastewater treatment. The novel contribution of this study lies in the successful demonstration of the nopal cactus's fibrous residue (NFRP), a previously discarded, high-volume agro-industrial waste stream, as a synergistic bio-flocculant. This work explicitly departs from resource-intensive mucilage extraction by utilizing the bulk, dried structural components, making the approach intrinsically simpler, cheaper, and highly scalable, thereby establishing a direct path toward a zero-waste process for cactus-processing industries. The findings prove that a single natural replacement for AS is not technically viable; instead, these materials offer selective high performance, with the agave powder (AP) achieving a turbidity removal percentage of 97.76 ± 2.180% at its optimal dose (20 mg/L). The combined treatment by nopal fibrous residue powder with bentonite demonstrated the most impactful progress, achieving the highest COD removal percentage in the entire study, at 92.13 ± 0.398%. This value exceeds the performance of the chemical standard AS (≈ 88.5%), establishing the nopal fibrous residue powder–based combination as the optimal solution for high organic load reduction. This technical breakthrough directly challenges the dominance of synthetic chemicals in this specific treatment objective and validates the engineering relevance of utilizing the fibrous residue.

FUTURE PERSPECTIVE

While this study successfully demonstrated the technical efficacy of natural coagulants at a laboratory scale, the transition to industrial application requires a strategic shift toward pilot-scale validation. This next phase must prioritize the safety characterization and ultimate fate of the resulting composite sludge, a step essential for demonstrating the project's comprehensive value within a sustainable framework. Unlike the sludge generated by aluminium sulphate (AS), which often contains persistent chemical residues, the byproduct of agave and nopal-based treatment is primarily composed of biodegradable organic matter and inert minerals. This unique composition strategically positions the composite as a prime candidate for circular economy pathways, moving beyond simple disposal toward a zero-waste narrative. Future investigations should formally evaluate two specific beneficial reuse routes: the application of the sludge as a non-synthetic soil amendment, leveraging its captured total ammoniacal nitrogen and mineral content, and its suitability for anaerobic digestion to produce renewable methane (biogas). Furthermore, detailed life-cycle assessments (LCA) and economic analyses are required to quantify the long-term environmental and financial benefits of replacing synthetic chemicals with agricultural residues across varying seasonal conditions.

DECLARATION

During the preparation of this work the author(s) used [Gemini] in order to help formulate some ideas and translate in English. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

AVAILABILITY OF DATA AND MATERIALS

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

COMPETING INTERESTS

The authors declare that they have no competing interests.

FUNDING

No sources of funding to declare.

AUTHOR CONTRIBUTIONS

BKRM: supervised the study, validated the results and wrote the manuscript. CFA: elaborated the methodology, validated the results and reviewed the manuscript. BM: helped with the analysis part and the writing for the manuscript. CFFZ: validated the results, and discussed them. RZ: executed the laboratory studies. BL executed the laboratory studies.

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APPENDIX

Table A1. Variation of turbidity, pH, and conductivity with aluminium sulphate increasing doses

AS (mg/L)	pH	Conductivity (µS/cm)	Turbidity (NTU)	TRP %
0	7.72	941	93	/
20	8.76	580	33.43	64.1
40	8.7	947	24.61	73.5
60	8.73	934	19.47	79.1
80	8.7	929	17.31	81.4
100	8.79	933	10.83	88.4
120	8.81	909	10	89.2
140	8.8	926	8.34	91.0
150*	8.81	922	6.91	92.6**
160	8.82	919	7.07	92.4
170	8.83	925	10.2	89
Initial COD = 500 mg/L		$COD_{optimal}$ = 57.6 mg/L CODR = 88.5 %		
Initial TAN = 72 mg/L		$TANR_{optimal}$ = 36 mg/L TANR = 50 %		

*Optimal dose **Highest TRP

Table A2. Variation of turbidity, pH, and conductivity with bentonite increasing doses

BN (mg/L)	pH	Conductivity (µS/cm)	Turbidity (NTU)	TRP %
0	7.59	905	85	/
10	8.62	990	14.47	83
20	8.7	975	9.37	89
30	8.66	972	8.61	89.9
40	8.68	969	9.16	89.2
50	8.73	963	7.07	91.7
60*	8.84	952	5.02	94.1**
70	8.69	964	6.88	91.9
80	8.67	966	7.8	90.8
90	8.71	981	8.26	90.3
Initial COD = 500 mg/L		$COD_{optimal}$ = 124 mg/L CODR = 75.2 %		
Initial TAN = 72 mg/L		$TANR_{optimal}$ = 36 mg/L TANR = 50 %		

*Optimal dose **Highest TRP

Table A3. Variation of turbidity, pH, and conductivity with eucalyptus leaf increasing doses

ELP (mg/L)	pH	Conductivity (µS/cm)	Turbidity (NTU)	TRP %
0	7.63	903	86	/
10	8.61	987	26.05	69.7
20	8.73	973	14.64	83.0
30	8.68	979	12.98	84.9
40	8.57	1 007	16.8	80.5
50	8.54	970	24.17	71.9
60	8.59	987	20.67	76.0
70	8.65	966	15.14	82.4
80	8.62	952	14.86	82.7
90*	8.64	953	10.16	88.2**
100	8.71	972	15.19	82.3
110	8.66	1 016	15.89	81.5
120	8.73	1 002	19.44	77.4
Initial COD = 500 mg/L		$COD_{Optimal}$ = 115.2 mg/L CODR = 77%		
Initial TAN = 72 mg/L		$TANR_{Optimal}$ = 72 mg/L TANR = 25 %		

*Optimal dose **Highest TRP

Table A4. Variation of turbidity, pH, and conductivity with agave powder increasing doses

AP (mg/L)	pH	Conductivity (µS/cm)	Turbidity (NTU)	TRP %
0	7.6	905	85	/
10	7.8	895	39	54.1
20*	7.9	838	0	100**
30	7.95	842	0.5	99.4
40	7.98	832	1.2	98.6
50	8	810	7	91.8
Initial COD = 500 mg/L		$COD_{optimal}$ = 220.8 mg/L CODR = 55.8 %		
Initial TAN = 72 mg/L		$TANR_{optimal}$ = 18 mg/L TANR = 75 %		

*Optimal dose **Highest TRP

Table A5. Variation of turbidity, pH, and conductivity with aluminium sulphate optimal dose combined with NFRP increasing doses

AS (mg/L)	NFRP (mg/L)	pH	Conductivity (µS/cm)	Turbidity (NTU)	TRP %
0	0	8.03	1 332	89.2	/
150	16.67	7.88	1 188	4.58	94.9
150	33.33	7.83	1 189	3.81	95.7
150	50.00	7.74	1 148	3.32	96.3
150	66.67	7.85	1 120	3.055	96.6
150	83.33	7.8	1 179	3.025	96.6
150	100.00*	7.74	1 195	2.815	96.8**
150	116.67	7.66	1 190	7.04	92.1
150	133.33	7.65	1 187	8.825	90.1
150	150.00	7.67	1 167	11.24	87.4
150	166.67	7.66	1 198	14.3	84.0
150	183.33	7.64	1 179	19.9	77.7
150	200.00	7.64	1 196	24.975	72.0
Initial COD = 492 mg/L			$COD_{optimal}$ = 51 mg/L CODR = 89.6%		
Initial TAN = 72 mg/L			$TANR_{optimal}$ = 15 mg/L TANR = 79%		

*Optimal dose **Highest TRP

Table A6. Variation of turbidity, pH, and conductivity with bentonite optimal dose combined with NFRP

BN (mg/L)	NFRP (mg/L)	pH	Conductivity (µS/cm)	Turbidity (NTU)	TRP %
0	0	7.79	1 101	72.5	/
60	33.33	7.82	1 105	26	64
60	66.67	7.91	1 109	13	82
60	100*	7.92	1 162.5	7.27	90**
60	133.33	7.98	1 172.5	10.27	86
Initial COD = 492 mg/L			$COD_{optimal}$ = 39 mg/L CODR = 92.07 %		
Initial TAN = 72 mg/L			$TANR_{optimal}$ = 20 mg/L TANR = 72%		

*Optimal dose **Highest TRP

Table A7. Trials for all the coagulants and flocculant

Coagulants/flocculants	Parameters	Initial	Trial 0	Trial 1	Trial 2	Trial 3	Std
AS (150 mg/L)	pH	7.72	8.81	8.92	8.85	9.1	0.128
	CE (µS/cm)	941	922	1200	1 120	1 462	223.625
	Turb (NTU)	93	6.91	7.8	10.52	5.92	1.977
BN (60 mg/L)	pH	7.59	8.84	8.72	8.89	8.75	0.079
	CE (µS/cm)	905	952	947	1 020	1 005	36.941
	Turb (NTU)	85	5.02	6.2	7.5	4.2	1.437
ELP (90 mg/L)	pH	7.63	8.64	8.72	8.82	8.69	0.076
	CE (µS/cm)	903	953	1023	1156	998	87.279
	Turb (NTU)	86	10.16	9.45	8.95	12.54	1.59
AP (20 mg/L)	pH	7.6	7.9	8.1	8.5	7.8	0.31
	CE (µS/cm)	905	838	955	889	852	52.297
	Turb (NTU)	85	0	2.5	4.2	0.9	1.849
AS (150 mg/L) + NFRP (100 mg/L)	pH	7.6	7.74	7.8	7.82	7.79	0.034
	CE (µS/cm)	905	1 195	1 165	1 202	1 166	19.27
	Turb (NTU)	85	2.815	3.5	2.95	3.1	0.296
BN (60 mg/L) + NFRP (100 mg/L)	pH	7.79	7.92	8.1	7.95	8.2	0.131
	CE (µS/cm)	1 101	1 162.5	1 258	1 195	1 302	62.577
	Turb (NTU)	72.5	7.27	8.2	6.52	8.9	1.043