



Coagulation Potential of Leaf-Based Natural Materials in the Treatment of Industrial Pharmaceutical Wastewater

Sathiya Priya A.† and Sundararaman S.

Department of Civil Engineering, Sri Manakula Vinayagar Engineering College, Puducherry, India

†Corresponding author: Sathiya Priya A.; sathiyapriya.smvec@gmail.com

Abbreviation: Nat. Env. & Poll. Technol.

Website: www.neptjournal.com

Received: 24-07-2025

Revised: 01-10-2025

Accepted: 06-10-2025

Key Words:

Pharmaceutical wastewater
Natural coagulants
Optimum dosage
COD concentration
Hydraulic retention time (HRT)

Citation for the Paper:

Sathiya Priya A. and Sundararaman S., 2026. Coagulation potential of leaf-based natural materials in the treatment of industrial pharmaceutical wastewater. *Nature Environment and Pollution Technology*, 25(2), B4380. <https://doi.org/10.46488/NEPT.2026.v25i02.B4380>

Note: From 2025, the journal has adopted the use of Article IDs in citations instead of traditional consecutive page numbers. Each article is now given individual page ranges starting from page 1.



Copyright: © 2026 by the authors

Licensee: Technoscience Publications

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

ABSTRACT

The growing demand for healthcare and population increase have accelerated the pharmaceutical industry, resulting in large-scale drug production processes. Consequently, partially or fully treated effluents are often released into the environment, posing risks to both ecosystems and human health. Pharmaceutical wastewater, particularly antibiotics, significantly contaminates aquatic habitats. This study investigated the use of plant-based natural coagulants (NC) as a low-cost, sustainable, and eco-friendly alternative to synthetic chemicals for the treatment of industrial pharmaceutical wastewater. Among the various natural coagulants, *Moringa oleifera* (moringa leaves) and *Mangifera indica* (mango leaves) were selected for this study. Jar test experiments were performed by mixing a 3 mL stock solution of each coagulant with 1000 mL of pharmaceutical wastewater in a beaker. The treatment was conducted under varying hydraulic retention times (HRT) of 2, 4, 6, and 8 h using 150 µm coagulant powders. Parameters such as pH, turbidity, TS, total dissolved solids (TDS), total suspended solids (TSS), chemical oxygen demand (COD), alkalinity, phenolic compounds, and phosphate were analyzed. The results indicated that moringa leaf powder achieved the highest COD reduction of approximately 86% at an 8 h HRT. Furthermore, the treated coagulant residues were analyzed using FE-SEM and EDX to evaluate surface morphology and elemental composition before and after wastewater treatment.

INTRODUCTION

The pharmaceutical industry in India has evolved in recent times. This progress is mostly determined by the country's swiftly escalating population and the growing demand for healthcare products and amenities. Consequently, the manufacture of pharmaceutical products has also increased significantly to meet these mounting needs (Dafale et al. 2008). However, the intensification of pharmaceutical manufacturing has led to an equivalent increase in the production of industrial effluents. During the manufacturing process, large volumes of effluent are liquidated, encompassing a variety of chemical and pharmaceutical deposits. This wastewater is one of the primary contributors to industrial water pollution in India. According to reports, pharmaceutical wastewater accounts for approximately one-third of all water pollution associated with industrial discharges in the country (Maurya & Daverey 2018). The occurrence of injurious pharmaceutical compounds in wastewater poses a significant threat to the quality of natural water bodies, such as rivers, lakes, and groundwater sources. Additionally, wastewater disposed of by pharmaceutical industries regularly encompasses constituents such as antibiotics and organic pollutants. Regrettably, conservative treatment methods do not always succeed in eliminating all antibiotic residues from wastewater. The ability to remove pollutants often differs based on the treatment process employed and the scale of the pharmaceutical industry. Recent studies have explored sustainable and low-cost adsorbents for the removal of heavy metals from water. For example, Verma & Sachdeva (2025) investigated the use

of peanut hulls as a biosorbent for lead and demonstrated their potential in water purification applications. Similarly, Rajput et al. (2025) provided a comprehensive review of bioremediation techniques for heavy metal contamination, highlighting the role of biological approaches in mitigating environmental pollution. In some circumstances, wastewater is directly disposed of into nearby water bodies without suitable treatment. This practice can have severe negative effects on aquatic ecosystems. They also pose serious risks to human health, such as genotoxicity, hormonal disruption, and overall water toxicity (Desta & Bote 2021). To address this issue, alternative treatment methods have been explored. One promising method is biological action, which uses naturally occurring microorganisms to reduce contaminants in wastewater. In contrast to conventional chemical treatment procedures, biological methods offer a more environmentally friendly and cost-effective solution (Rana et al. 2017.). The use of biological treatment methods helps to reduce pollution in aquatic environments. It also reduces reliance on synthetic chemicals, making it a more sustainable and safer option for treating pharmaceutical wastewater. Thus, biological tactics not only support environmental fortification but also align with the goals of low-cost and effective wastewater treatment.

Orthodox treatment approaches have been extensively adopted to remove pharmaceutical impurities from wastewater. The commonly applied techniques include ozonation, reverse osmosis, activated carbon filtration, and flocculation. Furthermore, more progressive methods, such as membrane bioreactors (MBR) and advanced oxidation processes (AOPs), have been established to augment the efficiency of pharmaceutical waste removal. Despite the availability of these technologies, the complete removal of pharmaceutical drugs from wastewater remains a challenge. Their efficiency can vary depending on the type of pharmaceutical compound and treatment conditions. Monitoring the presence and concentration of these compounds in both water and wastewater treatment plants is a major challenge. This difficulty arises because pharmaceuticals entering wastewater treatment systems are often not fully metabolized by humans. Consequently, active pharmaceutical residues remain in the effluent and pass through the treatment process (Kebede et al. 2018). One of the chemical methods used in wastewater treatment is coagulation, which commonly uses coagulants such as aluminum sulfate (alum). Aluminum sulfate hydrolyses rapidly when added to an aqueous solution. It forms positively charged cationic species that interact with the negatively charged colloidal particles in wastewater. This interaction promotes microfloc formation through a process known as charge neutralization. However, these microflocs are typically small and fragile. They lack adequate structural integrity and are disposed to defiance when endangered by physical stress,

such as agitation or flow turbulence. In addition, the use of aluminum-based coagulants habitually results in residual metal ions in treated water. This can raise the health and environmental alarms, particularly if the metal concentration surpasses permissible limits. Tamarind fruit shells (TFS) used in a fixed-bed reactor can remove over 90% of malachite green dye from aqueous solutions under optimized flow rate, biosorbent size, and bed depth conditions, with bed efficiency exceeding 90% and effective regeneration using 0.5 N HCl and H₂SO₄ (Murugesan et al. 2022). Furthermore, the overall effectiveness of the process manages to be comparatively low under certain working conditions. These limits underscore the importance of selecting suitable coagulants and optimizing the coagulation–flocculation process to improve treatment performance. As research continues, more sustainable and effective alternatives to traditional chemical coagulants are being explored (Eri et al. 2018).

The coagulation process is used to react with organic compounds in raw wastewater and destabilize suspended particles. Finding alternative coagulants from natural sources that are more affordable and environmentally friendly is essential to solving chemical coagulant issues (Kakoi et al. 2016). Several plant-based natural coagulants have been investigated for wastewater treatment, including *Moringa oleifera*, water hyacinth, okra, fenugreek, banana pith, cassava, neem leaf, and acorn (Ali et al. 2009, Camacho et al. 2017, Sanmuga & Selvan 2014, Lanan et al. 2021, Kakoi et al. 2016, Lugo-Arias et al. 2020, Ahmad et al. 2021, Antov et al. 2018, Šćiban et al. 2009). Activated carbon from avocado seed waste has a good sorption capacity for manganese and chromium ions from contaminated water (Mabalane et al. 2024). Natural coagulants used to treat various wastewaters have shown good efficacy in eliminating turbidity, TSS, color, and COD. In this study, pharmaceutical wastewater was treated using *Moringa* and *Mango Leaves* as natural coagulants with Raw Industrial Pharmaceutical wastewater.

Therefore, the present study evaluates the coagulation potential of leaf-based natural materials, namely *Moringa oleifera* and *Mangifera indica*, for the treatment of raw pharmaceutical wastewater. The study examines changes in pH, turbidity, total solids, total dissolved solids, and chemical oxygen demand under different hydraulic retention times. FE-SEM and EDX analyses were also used to examine the surface morphology and elemental changes in the coagulant materials before and after treatment.

MATERIALS AND METHODS

Wastewater Sampling and Initial Characterization

Untreated pharmaceutical wastewater samples were obtained

directly from a pharmaceutical manufacturing facility before the wastewater entered the existing treatment plant (Fig. 1). This sampling point was selected to ensure that the collected samples represented the untreated effluent generated during pharmaceutical production processes.

Sampling was performed on two distinct days to account for possible fluctuations in effluent characteristics. The collected samples were designated as Sample 1 and Sample 2, corresponding to the respective days of collection. Both samples were subjected to physicochemical characterization to determine the basic quality of the untreated pharmaceutical wastewater. The analyzed parameters included pH, turbidity, total solids (TS), total dissolved solids (TDS), total suspended solids (TSS), volatile suspended solids (VSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), alkalinity, chloride, dissolved oxygen (DO), phosphate concentration, and phenolic compounds. The results of the initial characterization are presented in Table 1.

The physicochemical characteristics of the pharmaceutical wastewater varied considerably between Sample 1 and Sample 2. This variation may be attributed to differences in

daily production activities, the nature of raw materials used, and operational conditions within the facility. In the present study, Sample 1 was treated with moringa leaf powder, whereas Sample 2 was treated with mango leaf powder. Therefore, the treatment outcomes are interpreted with reference to the respective wastewater sample treated with each natural coagulant. The efficiency of each coagulant in reducing contaminants and improving wastewater quality was assessed through jar test experiments.

Preparation of Natural Coagulants

This study employed powdered natural coagulants derived from moringa (*Moringa oleifera*) and mango (*Mangifera indica*) leaves for the treatment of raw pharmaceutical wastewater. These plant-based materials were selected because of their reported adsorption and coagulation potential in wastewater treatment. Previous studies have indicated that the major mechanisms involved in coagulation using natural coagulants include polymer bridging and charge neutralization, which promote the aggregation of suspended particles and enhance floc formation and sedimentation (Aziz et al. 2023, Kumar et al. 2017, Nath et al. 2021).



Fig. 1: Photographic views of raw pharmaceutical wastewater collected from the industry.

Table 1: Initial physicochemical characteristics of pharmaceutical wastewater.

| Sl No | Parameters | Pharmaceutical wastewater Sample 1 | Pharmaceutical wastewater Sample 2 | Units |
|-------|---------------------------|------------------------------------|------------------------------------|--------------------|
| 1 | pH | 7.65 | 7.7 | - |
| 2 | Turbidity | 94 | 163 | NTU |
| 3 | Total solids | 1196 | 2000 | mg.L ⁻¹ |
| 4 | Suspended solids | 262 | 1392 | mg.L ⁻¹ |
| 5 | Total Dissolved Solids | 908 | 632 | mg.L ⁻¹ |
| 6 | Volatile suspended solids | 169 | 171 | mg.L ⁻¹ |
| 7 | Total alkalinity | 342 | 2499 | mg.L ⁻¹ |
| 8 | Chlorides | 167 | 391 | mg.L ⁻¹ |
| 9 | Dissolved oxygen | 3.2 | 3.7 | mg.L ⁻¹ |
| 10 | COD | 5547 | 5977 | mg.L ⁻¹ |
| 11 | BOD | 1100 | 1271 | mg.L ⁻¹ |
| 12 | Phosphate | 18 | 26 | mg.L ⁻¹ |
| 13 | Phenolic Compound | BLQ(LOQ:0.002) | BLQ(LOQ:0.002) | |

Note: * BLQ (LOQ: 0.002) Below the Limit of Quantification

Fresh moringa and mango leaves were collected from local trees. The collected leaves were thoroughly washed with water to remove dust and surface impurities. They were then dried naturally under direct sunlight for several days until complete dehydration was achieved (Fig. 2). The dried leaves were ground into fine powder using a mechanical grinder. The resulting powder was sieved through a 150 μm mesh to obtain a uniform particle size, which helped maintain consistency in dosage and treatment performance.

For stock solution preparation, 3 g of each powdered natural coagulant was measured and mixed with 100 mL of distilled water. The prepared suspension was mixed thoroughly to ensure proper dispersion of the powdered material. This stock solution was used in the jar test experiments for the treatment of pharmaceutical wastewater. The preparation process is shown in Fig. 3.

Natural plant-based coagulants contain compounds such as proteins, carbohydrates, polysaccharides, and amino acid-based polymers, which may contribute to particle destabilization and floc formation. In the case of moringa and mango leaves, these bioactive components can interact with suspended particles in wastewater, reduce particle surface charge, and promote aggregation. The resulting flocs become heavier and settle more easily during the sedimentation stage. Thus, the naturally occurring bioactive compounds in moringa and mango leaves support their potential application as natural coagulants in pharmaceutical wastewater treatment.

Moringa and mango leaves were selected as locally available, biodegradable, and plant-based natural materials

with potential coagulation and adsorption properties. The coagulation potential of moringa leaves is mainly associated with cationic proteins, which can neutralize negatively charged suspended particles and promote the formation of settleable flocs. Mango leaves contain compounds such as polyphenols, flavonoids, and tannins, which may contribute to coagulation through adsorption and charge-neutralization mechanisms. Both materials were therefore tested under selected jar test conditions to evaluate their ability to reduce turbidity, solids, and organic load from raw pharmaceutical wastewater.

Coagulation Experiment: Jar Test Procedure

To evaluate the coagulation efficiency of the selected natural coagulants, jar test experiments were conducted using moringa (*Moringa oleifera*) and mango (*Mangifera indica*) leaf powders. Stock solutions of both coagulants were prepared by mixing 3 g of dried and finely powdered leaf material of 150 μm particle size with 100 mL of distilled water. The prepared stock solution was used for dosage optimization and subsequent treatment experiments.

For the preliminary dosage optimization, different volumes of the coagulant stock solution, ranging from 1 to 6 mL, were added separately to six beakers, each containing 1000 mL of raw pharmaceutical wastewater. The beakers were placed in a jar test apparatus or flocculator, as shown in Fig. 4. The coagulation process was initiated by rapid mixing at 100–120 rpm for the first few minutes to ensure uniform dispersion of the coagulant throughout the wastewater. This was followed by slow mixing at 30–40 rpm to promote gentle particle collision, aggregation, and floc formation.



Fig. 2: Photographic view of dried leaf and powdered form of moringa and mango leaf of size 150 μm .



Fig. 3: Photographic view of the stock solution prepared by using mango and moringa leaves.

After the mixing process, the samples were allowed to settle undisturbed for 30 min. This settling period enabled the formed flocs to settle at the bottom of the beakers, leaving comparatively clearer supernatant.

Among the tested dosages, the addition of 3 mL of stock solution showed the best coagulation efficiency, based on visible floc formation, settling behavior, and reduction in measured parameters. Therefore, 3 mL was selected as the optimum dosage and used in subsequent experiments to evaluate the treatment performance of moringa and mango leaf coagulants at different hydraulic retention times. The treated samples were analyzed after 2, 4, 6, and 8 h of hydraulic retention time to determine changes in pH, turbidity, total solids, total dissolved solids, and chemical oxygen demand. The experimental values are reported as observed readings under the selected treatment conditions.

Analytical Methods

pH, turbidity, total solids (TS), total dissolved solids (TDS), and chemical oxygen demand (COD) were measured using standard analytical methods.

Total Solids

Total solids were determined by evaporating a measured volume of wastewater sample in a pre-weighed crucible and drying it to constant weight in an oven at 105°C. The total solids concentration was calculated using the following equation:

$$TS (mg.L^{-1}) = \frac{W_2 - W_1}{V}$$

Where W_1 is the weight of the empty crucible, W_2 is the weight of the crucible with dried residue, and V is the volume of the sample.

Total Dissolved Solids

For total dissolved solids determination, the wastewater sample was filtered through a glass fiber filter, and the filtrate was evaporated in a pre-weighed crucible. The residue was dried at 105°C until a constant weight was obtained. TDS was calculated using the following equation:

$$TDS (mg.L^{-1}) = \frac{W_2 - W_1}{V}$$

where W_1 is the weight of the empty crucible, W_2 is the weight of the crucible with filtrate residue, and V is the volume of the sample.

Chemical Oxygen Demand

Chemical oxygen demand was determined using the dichromate digestion method. The wastewater sample was digested using potassium dichromate ($K_2Cr_2O_7$) as the oxidizing agent in a COD digester. After digestion, the sample was cooled to room temperature, and the excess dichromate was titrated with ferrous ammonium sulfate. COD was calculated using the following equation:

$$COD (mg.L^{-1}) = \frac{(A - B) \times M \times 8000}{V}$$

Where A is the titrant value of the blank, B is the titrant value of the sample, M is the molarity of ferrous ammonium sulfate, and V is the volume of the sample.

COD Reduction

The percentage reduction in COD was calculated as:

$$COD \text{ reduction } (\%) = \frac{COD_{inlet} - COD_{outlet}}{COD_{inlet}} \times 100$$

FE-SEM and EDX Analysis

FE-SEM analysis was carried out to examine the surface morphology of moringa and mango leaf powders before and after treatment with pharmaceutical wastewater. FE-SEM



Fig. 4: Jar Test Apparatus.

has been widely used for examining the microstructural characteristics of biosorbent and natural coagulant materials (Dey et al. 2022). EDX analysis was performed along with FE-SEM to determine the elemental composition of the coagulant materials before and after treatment.

RESULTS AND DISCUSSION

Effect of Natural Coagulants on pH and Turbidity

The variation in pH and turbidity during the treatment of raw pharmaceutical wastewater using moringa and mango leaf powders is shown in Fig. 5. The pH value recorded for the wastewater treated with moringa leaf powder showed a generally stable trend over the contact duration. Although the pH decreased slightly with increasing hydraulic retention time (HRT), the decrease was gradual and not abrupt. The pH decreased from 7.65 in the raw sample to 7.47 after 8 h of treatment. This indicates that moringa leaf powder did not cause a major shift in the pH of the treated wastewater and maintained a relatively stable chemical environment during treatment.

The pH trend for the mango-treated wastewater was different. The pH values showed greater variation during the treatment period. The pH increased from 7.70 in the raw sample to 7.90 after 2 h, decreased to 7.10 after 4 h and 6.50 after 6 h, and then increased again to 7.90 after 8 h. This fluctuation may be associated with the differential release of organic constituents from mango leaf powder or interactions between the coagulant material and the wastewater matrix. The increase in pH after 6 h may indicate changes in the chemical composition of the treated sample during the later stage of the treatment.

A clear reduction in turbidity was observed for both natural coagulants. In the moringa-treated sample, turbidity decreased from 94 NTU to 27 NTU after 8 h of treatment, corresponding to a reduction of approximately 71.27%. In the mango-treated sample, turbidity decreased from 163 NTU to 61 NTU after 8 h, corresponding to a reduction

of approximately 62.57%. This decrease indicates that suspended solids and particulate impurities were removed through coagulation, floc formation, and sedimentation. The results presented in Fig. 5 show that both moringa and mango leaf powders reduced turbidity, although moringa showed greater turbidity reduction under the tested sample conditions.

Effect of Natural Coagulants on Total Solids and Total Dissolved Solids

The changes in total solids and total dissolved solids during treatment are presented in Fig. 6. In the wastewater treated with moringa leaf powder, total solids showed a continuous reduction with increasing HRT. The total solids decreased from 1196 mg.L⁻¹ in the raw sample to 1112 mg.L⁻¹ after 2 h, 1106 mg.L⁻¹ after 4 h, 987 mg.L⁻¹ after 6 h, and 973 mg.L⁻¹ after 8 h. This gradual reduction suggests the effective removal of suspended and settleable particulate matter through coagulation and sedimentation.

In the mango-treated sample, the total solids concentration also decreased, but the reduction was less pronounced. The total solids decreased from 2000 mg.L⁻¹ in the raw sample to 2000 mg.L⁻¹ after 2 h, 1910 mg.L⁻¹ after 4 h, 1841 mg.L⁻¹ after 6 h, and 1784 mg.L⁻¹ after 8 h. The trend indicates gradual improvement in solids removal with increasing HRT. However, because the initial total solids concentration of Sample 2 was higher than that of Sample 1, the results should be interpreted with reference to the respective sample treated with each coagulant.

The total dissolved solids showed a relatively smaller change in the moringa-treated sample. The TDS decreased from 908 mg.L⁻¹ initially to 906 mg.L⁻¹ after 2 h, 892 mg.L⁻¹ after 4 h, 874 mg.L⁻¹ after 6 h, and 859 mg.L⁻¹ after 8 h. This indicates that moringa leaf powder mainly contributed to the removal of suspended and colloidal material, while its effect on dissolved solids was comparatively limited.

In contrast, the mango-treated sample showed a different TDS pattern. The TDS increased from 632 mg.L⁻¹ initially to

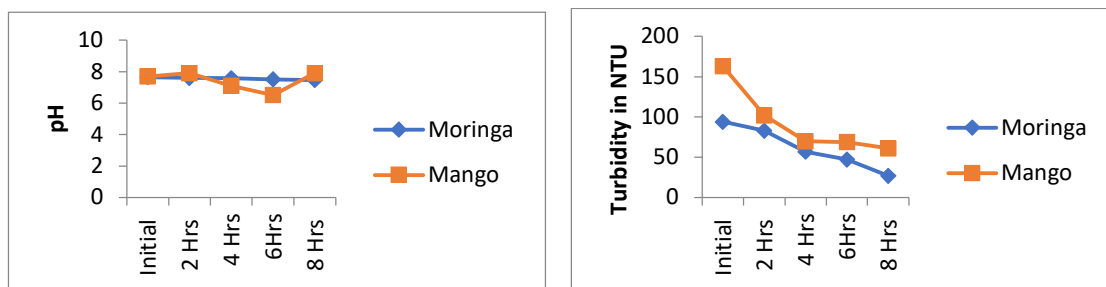


Fig. 5: Variations in pH and turbidity for the treatment of Raw Pharmaceutical wastewater samples 1 and 2 using the natural coagulants Moringa and Mango leaf powder.

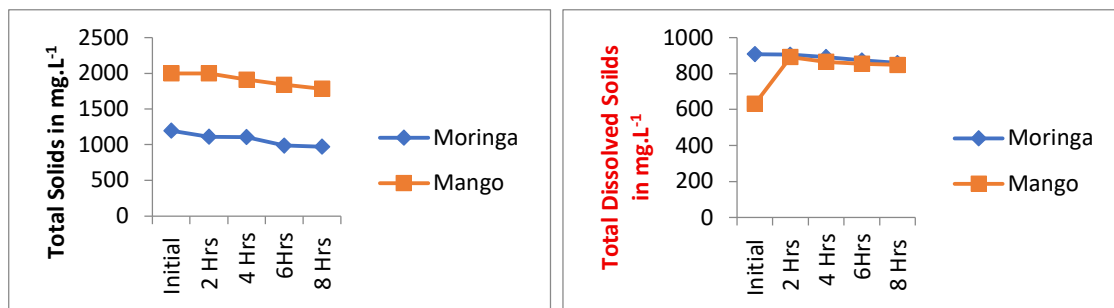


Fig. 6: Total solids and Total Dissolved solids for the treatment of Raw Pharmaceutical wastewater samples 1 and 2 by using the Natural coagulants Moringa and Mango leaf powder.

892 mg.L⁻¹ after 2 h, followed by a gradual decrease to 865 mg.L⁻¹ after 4 h, 855 mg.L⁻¹ after 6 h, and 849 mg.L⁻¹ after 8 h. The initial increase in TDS may be due to the release of soluble organic or inorganic constituents from mango leaf powder into the wastewater. The subsequent decrease suggests partial stabilization of dissolved constituents during the later stages of treatment.

Overall, the results indicate that both coagulants affected the solid content of the wastewater, but their influence was stronger on total solids than on total dissolved solids. Moringa-treated wastewater showed a more consistent decrease in total solids, whereas mango-treated wastewater showed higher variation in TDS during the treatment period.

Effect of Natural Coagulants on COD and COD Reduction

The variation in chemical oxygen demand during treatment is shown in Fig. 7, and the treatment performance of the natural coagulants is summarized in Table 2. COD is an important indicator of the organic load in wastewater, and its reduction reflects the ability of the treatment process to remove oxidizable organic matter.

In the moringa-treated sample, the COD concentration decreased progressively with increasing HRT. The initial COD concentration of Sample 1 was 5547 mg.L⁻¹. After treatment with moringa leaf powder, COD decreased to 3589 mg.L⁻¹ after 2 h, 2792 mg.L⁻¹ after 4 h, 1622 mg.L⁻¹ after 6 h, and 781 mg.L⁻¹ after 8 h. This corresponds to an overall COD reduction of approximately 86% at 8 h. The consistent decrease in COD suggests that moringa leaf powder promoted the removal of organic matter associated with suspended and colloidal fractions of the wastewater.

In the mango-treated sample, the COD reduction was comparatively lower. The initial COD concentration of Sample 2 was 5977 mg.L⁻¹. After treatment with mango leaf powder, COD decreased only slightly to 5976 mg.L⁻¹ after 2 h, 5307 mg.L⁻¹ after 4 h, 5299 mg.L⁻¹ after 6 h, and

5258 mg.L⁻¹ after 8 h. This corresponds to a COD reduction of approximately 12% after 8 h. The limited reduction suggests that mango leaf powder had lower efficiency in removing organic load under the tested conditions.

The better performance of moringa leaf powder may be associated with the presence of naturally occurring cationic polymers and bioactive compounds that help neutralize negatively charged particles in wastewater. This charge neutralization promotes particle destabilization, aggregation, and floc formation. The formed flocs settle more easily, thereby reducing suspended organic matter and contributing to COD reduction. Similar coagulation mechanisms involving natural polymeric coagulants have been reported by Nath et al. (2021).

The COD reduction trend also showed a time-dependent response. In the moringa-treated sample, COD reduction increased steadily from approximately 35% after 2 h to 50% after 4 h, 71% after 6 h, and 86% after 8 h. In contrast, the mango-treated sample showed negligible reduction at 2 h and only limited improvement up to 12% after 8 h. These findings indicate that increased HRT improved treatment efficiency, particularly for the moringa-treated wastewater.

However, it is important to note that Sample 1 and Sample 2 had different initial wastewater characteristics and were treated with different coagulants. Therefore, the results should not be interpreted as a strictly controlled direct comparison between moringa and mango leaf powders. Instead, the findings indicate that moringa leaf powder showed stronger treatment performance under the tested sample conditions, while mango leaf powder showed moderate turbidity reduction but limited COD removal.

FE-SEM and EDX Characterization of Moringa and Mango Leaf Powders

FE-SEM and EDX analyses were carried out to examine the surface morphology and elemental composition of moringa and mango leaf powders before and after treatment with

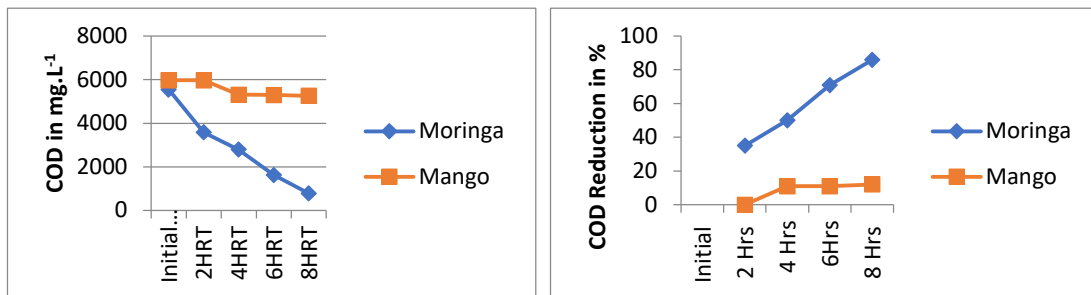


Fig. 7: Variations of COD for the treatment of raw pharmaceutical wastewater samples 1 and 2 by using the natural coagulants moringa and mango leaf powder.

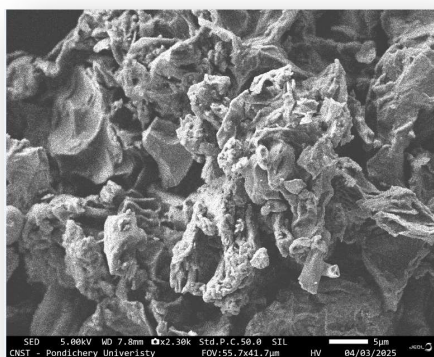
Table 2: Treatment performance of natural coagulants (moringa and mango leaves) on pharmaceutical wastewater.

| Parameters | Sample 1(Raw) | Sample 2(Raw) | Sample 1 treated with NC Moringa Leaf Powder | Sample 2 treated with NC Mango Leaf Powder |
|-----------------------|-------------------------|-------------------------|--|--|
| Turbidity | 94 NTU | 163 NTU | 27 NTU | 61 NTU |
| COD | 5547 mg.L ⁻¹ | 5977 mg.L ⁻¹ | 781 mg.L ⁻¹ | 5258 mg.L ⁻¹ |
| Turbidity Reduction % | - | - | 71.27% | 62.6 |
| COD Reduction % | - | - | 86 | 12 |

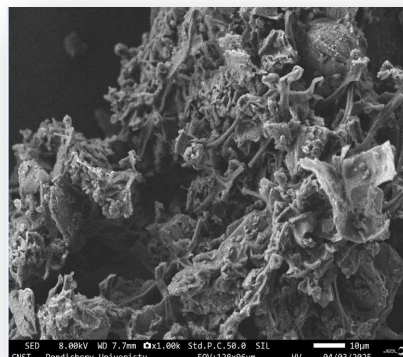
industrial pharmaceutical wastewater. The morphological changes observed in moringa and mango leaf powders are presented in Figs. 8 and 10, while the corresponding EDX spectra are shown in Figs. 9 and 11.

Fig. 8(a) shows the microstructural morphology of untreated *Moringa oleifera* leaf powder. The surface appeared porous, irregular, and folded, with visible crevices and cavities. These structural features may provide surface sites for pollutant attachment and support adsorption and coagulation processes. The folded and flake-like layers may also help in particle binding, especially during the removal of suspended solids and organic contaminants from wastewater.

After treatment with pharmaceutical wastewater, the moringa leaf powder showed visible changes in surface morphology, as shown in Fig. 8(b). The particles appeared more interconnected, clustered, and fused. This aggregation may be associated with the interaction of wastewater constituents with natural biopolymers such as proteins and polysaccharides present in the leaf material. These biopolymers may act as bridging agents, promoting particle agglomeration, floc formation, and sedimentation. The observed structural changes support the role of moringa leaf powder in reducing turbidity and COD through coagulation and settling.



(a)



(b)

Fig. 8: FE SEM image of moringa leaves (a) before and (b) after treatment with industrial pharmaceutical wastewater.

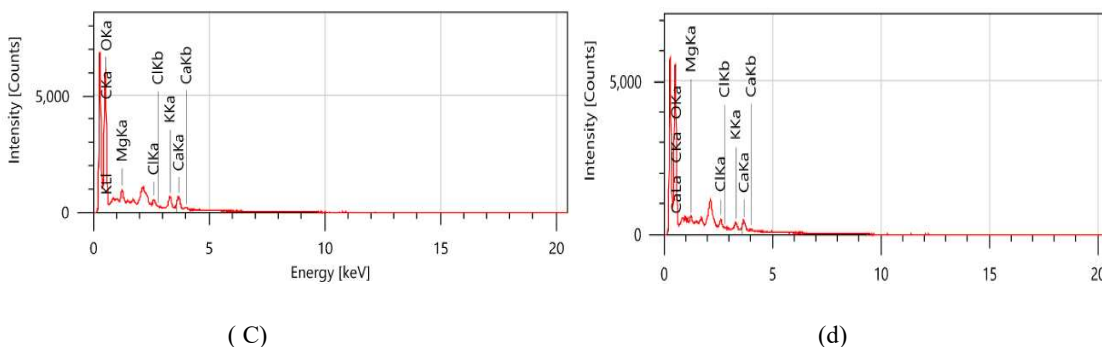


Fig. 9: EDX analysis of moringa leaves (c) before and (d) after treatment with industrial pharmaceutical wastewater.

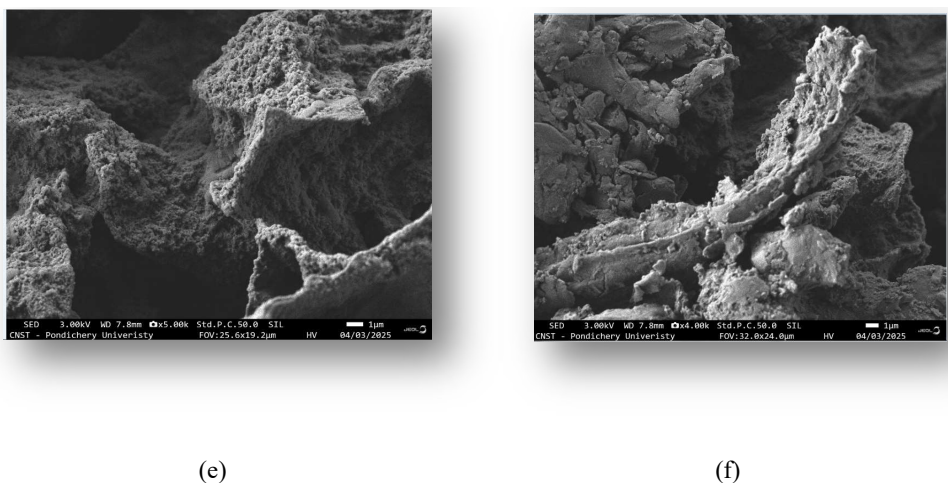


Fig. 10: FE SEM image of mango leaves before (e) and after (f) treatment with industrial pharmaceutical wastewater.

The EDX analysis of moringa leaf powder before and after treatment is shown in Fig. 9. Before treatment, the elemental composition of moringa leaf powder consisted mainly of carbon, oxygen, magnesium, chlorine, potassium, and calcium. The elemental content was C 30.84%, O 54.89%, Mg 1.20%, Cl 2.21%, K 2.57%, and Ca 4.64%. After treatment, the values changed to C 31.78%, O 57.89%, Mg 1.80%, Cl 1.88%, K 4.73%, and Ca 5.86%. These changes indicate interaction between the moringa leaf surface and wastewater constituents during treatment.

Fig. 10(e) shows the FE-SEM image of untreated mango leaf powder. The surface appeared porous, rough, and irregular, with ridges, cavities, and loosely packed granules. These surface features suggest that mango leaf powder may provide active sites for adsorption and interaction with suspended impurities. However, the structure appeared less compact and less fibrous than that of moringa leaf powder, which may partly explain its lower treatment performance under the tested conditions.

After treatment, the mango leaf powder showed structural changes, including compacted residues, clustered particles, and layered surface deposits, as shown in Fig. 10(f). Some regions showed a coating-like appearance, which may be due to the adsorption of organic and inorganic constituents from the wastewater. These changes indicate that mango leaf powder interacted with pollutants during treatment. However, the extent of surface aggregation appeared less dense and less uniform than that observed for moringa, which is consistent with the lower COD removal observed in the mango-treated sample.

The EDX analysis of mango leaf powder is shown in Fig. 11. Before treatment, the elemental composition consisted of C 33.33%, O 60.73%, Si 0.78%, K 1.21%, and Ca 3.95%. After treatment, the composition changed to C 41.86%, O 42.49%, Mg 0.97%, Si 10.82%, Cl 0.71%, K 0.87%, and Ca 2.29%. These changes suggest elemental exchange and surface interaction between mango leaf powder and wastewater constituents. However, despite these changes, mango leaf powder showed limited COD

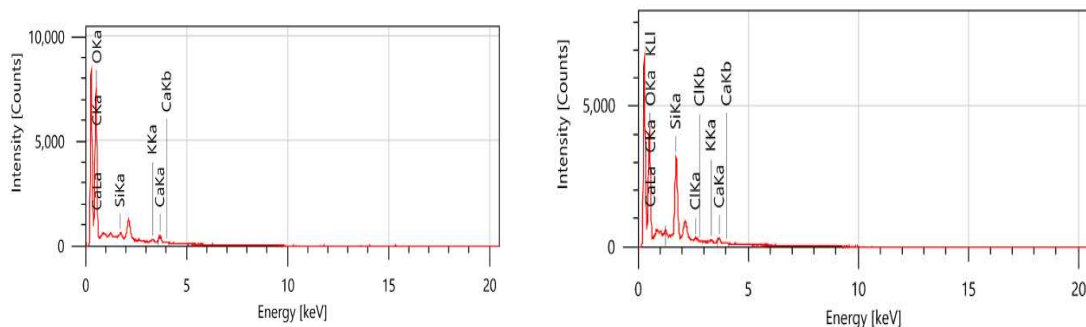


Fig. 11: EDX analysis of mango leaves before (g) and after (h) treatment with industrial pharmaceutical wastewater.

reduction compared with moringa under the tested conditions.

CONCLUSIONS

The present study evaluated the coagulation potential of moringa (*Moringa oleifera*) and mango (*Mangifera indica*) leaf powders for the treatment of raw pharmaceutical wastewater. The collected wastewater samples showed different initial characteristics, with turbidity values of 94 NTU and 163 NTU and COD values of 5547 mg.L⁻¹ and 5977 mg.L⁻¹ for Sample 1 and Sample 2, respectively.

Under the tested conditions, moringa leaf powder reduced turbidity from 94 NTU to 27 NTU and COD from 5547 mg.L⁻¹ to 781 mg.L⁻¹ after 8 h of HRT. This corresponded to approximately 71.27% turbidity reduction and 86% COD reduction. Mango leaf powder reduced turbidity from 163 NTU to 61 NTU, corresponding to approximately 62.6% turbidity reduction, but COD reduction was limited to approximately 12% after 8 h.

FE-SEM and EDX analyses showed visible changes in surface morphology and elemental composition of the leaf powders after wastewater treatment, indicating interaction between the natural coagulants and wastewater constituents. The moringa-treated sample showed stronger reduction in turbidity and COD under the tested sample conditions. However, since moringa and mango powders were applied to different wastewater samples, the findings should be interpreted cautiously rather than as a fully controlled direct comparison.

Overall, the study suggests that moringa leaf powder has potential as a low-cost natural coagulant for reducing turbidity and organic load in pharmaceutical wastewater. Future studies should test both coagulants on the same wastewater sample, include replicate experiments, optimize mixing and dosage conditions, and evaluate the treated effluent against regulatory discharge standards.

REFERENCES

- Ahmad, A., Abdullah, S.R.S., Hasan, H.A., Othman, A.R. and Ismail, N.I., 2021. Plant-based versus metal-based coagulants in aquaculture wastewater treatment: effect of mass ratio and settling time. *Journal of Water Process Engineering*, 43, pp.102269. [DOI]
- Ali, E.N., Muyibi, S.A. and Salleh, H.M., 2009. Moringa oleifera seeds as a natural coagulant for water treatment. In: *Proceedings of the Thirteenth International Egyptian Water Technology Conference*, Cairo, Egypt, pp.123-130.
- Antov, M.G., Šćiban, M.B., Prodanović, J.M., Kukić, D.V., Vasić, V.M., Đorđević, T.R. and Milošević, M.M., 2018. Common oak (*Quercus robur*) acorn as a source of natural coagulants for water turbidity removal. *Industrial Crops and Products*, 117, pp.340-346. [DOI]
- Aziz, F., Din, I., Khan, F., Manan, P., Sher, A. and Hakim, S., 2023. Treatment of fluoride-contaminated water using mango (*Mangifera indica*) leaves powder as an adsorbent. *Current Research in Green and Sustainable Chemistry*, 6, pp.100359. [DOI]
- Camacho, F.P., Sousa, V.S., Bergamasco, R. and Teixeira, M.R., 2017. The use of Moringa oleifera as a natural coagulant in surface water treatment. *Chemical Engineering Journal*, 320, pp.200-210.
- Dafale, N., Rao, N.N., Meshram, S.U. and Wate, S.R., 2008. Decolorization of azo dyes and simulated dye bath wastewater using acclimatized microbial consortium–biostimulation and halo tolerance. *Bioresource Technology*, 99(15), pp.6789-6798.
- Desta, W.M. and Bote, M.E., 2021. Wastewater treatment using a natural coagulant (*Moringa oleifera* seeds): optimization through response surface methodology. *Heliyon*, 7(5), pp.e07012.
- Dey, S., Sreenivasulu, A., Veerendra, G.T.N., Manoj, A.V.P. and Haripavan, N., 2022. Synthesis and characterization of mango leaves biosorbents for the removal of iron and phosphorous from contaminated water. *Applied Surface Science Advances*, 11, pp.100292. [DOI]
- Eri, I.R., Hadi, W. and Slamet, A., 2018. Clarification of pharmaceutical wastewater with Moringa oleifera: optimization through response surface methodology. *Journal of Ecological Engineering*, 19(3), pp.126-134. [DOI]
- Kakoi, B., Kaluli, J.W., Ndiba, P. and Thiong'o, G., 2016. Banana pith as a natural coagulant for polluted river water. *Ecological Engineering*, 95, pp.456-464.
- Kebede, T.G., Dube, S. and Nindi, M.M., 2018. Removal of non-steroidal anti-inflammatory drugs (NSAIDs) and carbamazepine from wastewater using water-soluble protein extracted from Moringa stenopetala seeds. *Journal of Environmental Chemical Engineering*, 6(2), pp.3095-3103. [DOI]
- Kumar, V., Othman, N. and Asharuddin, S., 2017. Applications of natural coagulants to treat wastewater – a review. *MATEC Web of Conferences*, 103, pp.06016. [DOI]

- Lanan, F.A.B.M., Selvarajoo, A., Sethu, V. and Arumugasamy, S.K., 2021. Utilization of natural plant-based fenugreek (*Trigonella foenum-graecum*) coagulant and okra (*Abelmoschus esculentus*) flocculant for palm oil mill effluent. *Journal of Environmental Chemical Engineering*, 9(4), pp.105678.
- Lugo-Arias, J.E., Lugo-Arias, E., Ovallos-Gazabon, D., Arango, J., de La Puente, M. and Silva, J., 2020. Effectiveness of the mixture of nopal and cassava starch as clarifying substances in water purification: a case study in Colombia. *Heliyon*, 6(6), pp.e04296. [DOI]
- Mabalane, K., Shooto, N.D. and Thabede, P.M., 2024. A novel permanganate and peroxide carbon-based avocado seed waste for the adsorption of manganese and chromium ions from water. *Case Studies in Chemical and Environmental Engineering*, 10, pp.100782. [DOI]
- Maurya, S. and Daverey, A., 2018. Evaluation of plant-based natural coagulants for municipal wastewater treatment. *3 Biotech*, 8(1), pp.1-9. [DOI]
- Murugesan, S.R., Sivakumar, V., Velusamy, S., Ravindiran, G., Sundararaj, P., Maruthasalam, V., Thangavel, R., Ramasamy, G.S., Panneerselvam, M. and Periyasamy, S., 2022. Biosorption of malachite green from aqueous phase by tamarind fruit shells using FBR. *Advances in Materials Science and Engineering*, 2022, pp.8565524. [DOI]
- Nath, A., Mishra, A. and Pande, P.P., 2021. A review natural polymeric coagulants in wastewater treatment. *Materials Today: Proceedings*, 46, pp.6113-6117. [DOI]
- Rajput, P., Benjwal, S. and Pandey, R., 2025. A comprehensive review on the role of bioremediation in heavy metal contamination. *Nature Environment and Pollution Technology*, 24(1), pp.236-245.
- Sanmuga, P. E. and Selvan, S.P., 2014. Water hyacinth (*Eichhornia crassipes*)-an efficient and economic adsorbent for textile effluent treatment-a review. *Arabian Journal of Chemistry*, 7(4), pp.456-465. [DOI]
- Šćiban, M., Klačnja, M., Antov, M. and Škrbić, B., 2009. Removal of water turbidity by natural coagulants obtained from chestnut and acorn. *Bioresource Technology*, 100(24), pp.6639-6643. [DOI]
- Rana, R.S., Singh, P., Kandari, V., Singh, R., Dobhal, R. and Gupta, S., 2017. A review on characterization and bioremediation of pharmaceutical industries' wastewater: an Indian perspective. *Applied Water Science*, 7(1), pp.123-135.
- Verma, M. and Sachdeva, S., 2025. Investigating the effectiveness of peanut hull as biosorbent of lead (Pb) from water. *Nature Environment and Pollution Technology*, 24(2), pp.1-10. [DOI]