Moringa oleifera Seed Extract as a Natural Coagulant for Water Purification: An Eco-Friendly Alternative to Alum

Lt Rajat S. Yadav[1*] Shreya Bhisekar* RiyaWade*

[1*] *Assistant Professor, Kavikuguru Institute of Technology and Science, Ramtek, Maharashtra, India*
[2] *Student, Civil Engineering Department, Kavikuguru Institute of Technology and Science, Ramtek, Maharashtra, India*

Abstract: *Water contamination is a global public health challenge, particularly in developing nations where conventional chemical coagulants such as aluminium sulphate (alum) remain the predominant treatment option. While effective, alum has been associated with elevated residual aluminium concentrations in treated water, a factor linked to neurotoxic effects including Alzheimer's disease and generate large volumes of non-biodegradable sludge. This study investigates the coagulation–flocculation performance of Moringa oleifera Lam. seed extract as a bio-coagulant for surface water treatment, with direct comparison against alum across a range of turbidity levels (50–500 NTU). Jar tests were conducted at optimized dosage (50–200 mg/L), pH (6–8), and rapid mixing conditions. Results demonstrate that M. oleifera seed extract achieved turbidity removal efficiencies of 85–98%, colour removal of 80–95%, and microbial load reduction of up to 3 log units, results broadly comparable to alum. Critically, the natural coagulant exhibited superior performance at lower initial turbidities, produced 40–60% less sludge, is entirely biodegradable, and left no toxic residuals. Physicochemical parameters including pH, dissolved oxygen, biochemical oxygen demand (BOD), total dissolved solids (TDS), and total suspended solids (TSS) were monitored before and after treatment. The findings confirm M. oleifera as a technically viable, cost-effective, and environmentally sustainable replacement for alum in water treatment—particularly suitable for rural and resource-constrained settings.*

Keywords: *Moringa oleifera; natural coagulant; water purification; turbidity removal; alum; coagulation–flocculation; bio-coagulant; sustainable water treatment*

1. Introduction

Access to safe drinking water remains one of the most pressing challenges of the 21st century. According to the World Health Organization (WHO, 2023), approximately 2 billion people worldwide lack access to safely managed drinking water services. In developing countries including India, untreated or inadequately treated surface water is a primary vector for waterborne diseases such as cholera, typhoid, and dysentery, collectively responsible for over 1.6 million deaths annually.

Coagulation–flocculation is a foundational unit process in conventional water treatment, facilitating the aggregation and subsequent sedimentation of colloidal particles, suspended solids, natural organic matter (NOM), and pathogenic microorganisms. Aluminium sulphate (alum, $Al_2(SO_4)_3 \cdot 18H_2O$) has historically dominated as the coagulant of choice due to its ready commercial availability, low cost, and established effectiveness. However, growing scientific and regulatory concern over residual aluminium in treated water (WHO guideline: 0.2 mg/L), the generation of large quantities of aluminium-rich sludge, and the potential link between chronic aluminium exposure and neurological disorders has prompted the search for alternative coagulants.

Natural, plant-based coagulants offer a promising alternative paradigm. Among candidate species, Moringa oleifera Lam. (family Moringaceae), commonly known as the drumstick tree or horseradish tree, has received the most substantial scientific attention. Native to the sub-Himalayan regions of India, M. oleifera is cultivated widely across tropical and subtropical Africa, Asia, and Latin America. Its seeds contain a cationic polyelectrolyte protein—most notably the dimeric protein MO2.1 (molecular weight ~13.5 kDa) that functions as an effective coagulant by destabilizing colloidal particles through charge neutralisation and bridging mechanisms.

Numerous bench-scale and pilot-scale studies have demonstrated the efficacy of M. oleifera seed extract in removing turbidity, colour, bacteria, and organic matter from surface water, wastewater, and grey water. However, systematic comparisons with alum under controlled jar-test conditions, spanning a wide turbidity range and evaluating a comprehensive suite of water quality parameters, remain relatively limited in the published literature. Furthermore, few studies have quantitatively assessed sludge production, residual coagulant concentration, and cost implications within the same experimental framework.

The present study addresses these gaps. The objectives are: (i) to characterise the coagulation performance of M. oleifera seed extract across a range of water turbidity levels; (ii) to compare its efficacy directly with aluminium sulphate; (iii) to evaluate key treated-water quality parameters; (iv) to quantify sludge production and residual coagulant concentrations; and (v) to conduct a preliminary cost and sustainability analysis. The ultimate aim is to generate a robust evidence base supporting the adoption of M. oleifera as a sustainable, low-cost coagulant in community-scale water treatment, particularly in rural India and comparable settings.

2. Literature Review

2.1 Conventional Coagulation Using Alum

Alum acts as a coagulant through a dual mechanism: hydrolysis to form aluminium hydroxide precipitates ($Al(OH)_3$) that sweep-floc suspended particles, and the generation of cationic Al^{3+} species that neutralise the negative surface charge of colloids, reducing the energy barrier to aggregation. Optimal performance is typically achieved at pH 6.5–7.5. Studies by Edzwald and Haarhoff (2011) established that alum is highly effective at turbidities above 100 NTU but shows reduced efficiency at low turbidities (<10 NTU) without additional coagulant aids.

Concerns over alum use include: (a) residual Al^{3+} concentrations exceeding WHO guidelines when overdosed or when treated water pH drifts; (b) the production of large, non-biodegradable aluminium hydroxide sludge volumes requiring specialised disposal; (c) significant pH depression of the treated water, often requiring lime addition; and (d) importation costs in developing nations where alum is not locally produced. Studies by Flaten (2001) and Yokel and McNamara (2001) have provided epidemiological and toxicological evidence linking chronic aluminium exposure to Alzheimer's disease, catalysing regulatory interest in lower-residual alternatives.

2.2 Moringa oleifera as a Bio-coagulant

The coagulation activity of M. oleifera seeds was first scientifically documented by Jahn (1988), who reported effective turbidity removal from Nile River water using crude seed preparations. Subsequent work by Muyibi and Evison (1995) demonstrated dose-dependent turbidity removal comparable to alum under similar conditions.

The active coagulant agent has been identified as a water-soluble cationic polypeptide. Gassenschmidt et al. (1995) isolated a 6.5 kDa peptide (MO2.1) with a high proportion of positively charged amino acid residues (arginine, lysine), which confers the strong coagulating activity. More recent proteomic characterisation by Madrona et al. (2010) and Camacho et al. (2017)

confirmed that several proteins in the 10–14 kDa range contribute to coagulation, primarily through adsorption and bridging mechanisms rather than sweep flocculation.

Laboratory studies have reported turbidity removal efficiencies of 70–99% across varied raw water qualities. Nkurunziza et al. (2009) demonstrated 99% turbidity removal from highly turbid water (>300 NTU) using 25 mg/L of M. oleifera seed extract. Okuda et al. (2001) found that the coagulant activity was significantly enhanced by salt extraction (NaCl solution) compared to direct water extraction, due to improved protein dissolution. Maikokera and Kwaambwa (2007) used fluorescence spectroscopy to confirm that the protein adopts a stable tertiary structure conducive to particle bridging.

Beyond turbidity, several studies have reported removal of bacteria (Escherichia coli, total coliforms), natural organic matter, heavy metals (lead, cadmium), and fluoride by M. oleifera. Notably, Mehta and Bhatt (2018) reported 2.5–3 log reductions in E. coli using optimised seed extract concentrations, a particularly important property for point-of-use treatment in rural settings.

Comparative studies with alum show broadly similar turbidity removal at moderate-to-high turbidities, with M. oleifera showing advantages at lower turbidities and producing significantly less sludge (Muyibi et al., 2001; Bichi, 2013). The major limitation noted in the literature is the potential for increased DOC leaching from the seed extract itself, which may elevate BOD in treated water and provide a substrate for microbial regrowth. Salt-extracted protein preparations largely mitigate this concern.

3. Materials and Methods

3.1 Collection and Preparation of Moringa oleifera Seed Extract

Dry and mature Moringa oleifera seeds were collected from trees available at the KITS Ramtek campus, Maharashtra. The outer shell of the seed was removed by hand, and the inner seed kernel was dried in sunlight for about 2 days. After drying, the kernel was crushed into a fine powder using a mortar and pestle. This powder was then stored in a clean, sealed plastic bag at room temperature until use.

To prepare the extract, 10 grams of seed powder was mixed with 50 mL of salt water (0.5 M NaCl solution) in a beaker. This mixture was stirred continuously for 30 minutes using a magnetic stirrer. After stirring, it was filtered through filter paper (Whatman No. 4) to remove solid particles. The clear liquid obtained is the Moringa seed extract, which works as a natural coagulant. This extract was prepared fresh each time and used within 4 hours to keep it effective. For experiments, it was further diluted with distilled water to get different doses ranging from 50 to 200 mg/L.

3.2 Preparation of Turbid Water Sample

To get consistent results in the laboratory, turbid water was prepared artificially by mixing kaolin clay powder in clean distilled water. Kaolin is a fine white clay commonly used in labs to simulate muddy or turbid river water. Four different levels of turbidity were prepared: 50, 100, 200, and 500 NTU (NTU stands for Nephelometric Turbidity Units — higher the number, cloudier the water). The pH of all samples was kept at 7.0, which is neutral, and the temperature was maintained at around 25°C during all tests.

3.3 Alum Preparation

Alum (aluminium sulphate) solution was prepared by dissolving alum powder in distilled water to make a 1% solution (10 g per litre). From this stock solution, working doses of 50 to 200 mg/L were prepared for comparison with the Moringa extract. The pH of the alum solution was adjusted to 7.0 before use. Alum is the chemical currently used in most water treatment plants, so this comparison helps us understand how well Moringa works in its place.

3.4 Jar Test Procedure

The jar test is a simple and widely used laboratory method to check how well a coagulant works in removing dirt, cloudiness, and impurities from water. It simulates what happens in a real water treatment plant. In this study, the jar test was used to test both Moringa seed extract and alum for their ability to remove turbidity, colour, and other impurities — including checking the clarity of water after treatment.

A standard jar test machine with six paddles was used. For each test, 1 litre of turbid water was taken in a beaker. The coagulant (either Moringa extract or alum) was added at different doses (50, 75, 100, 125, 150, and 200 mg/L). The test followed three steps: (1) Fast mixing at 200 rpm for 2 minutes — this helps the coagulant spread evenly in water and start sticking to dirt particles; (2) Slow mixing at 30 rpm for 20 minutes — this allows small particles to join together and form bigger clumps called flocs; (3) Still settling for 30 minutes — the flocs settle down at the bottom due to gravity. After settling, a small water sample (50 mL) was carefully taken from just below the surface for testing.

The jar test was repeated at different pH levels (5, 6, 7, 8, and 9) and at all four turbidity levels to understand how conditions affect performance. Each test was done three times to make sure the results were reliable.

3.5 Water Quality Testing Methods

After the jar test, the collected water samples were tested for several quality parameters to check how clean the water had become. The following simple tests were carried out:

Turbidity (cloudiness of water) was measured using a turbidity meter. Colour of water was checked using a spectrophotometer. pH (acidity or basicity) was measured using a pH meter. Dissolved Oxygen (DO) shows how much oxygen is present in water and was measured using a DO meter. BOD (Biochemical Oxygen Demand) tells how much organic pollution is in the water — lower is better. TDS (Total Dissolved Solids) and TSS (Total Suspended Solids) were measured by filtering and drying water samples and weighing them. Bacterial count (total coliform bacteria) was checked using a standard MPN test to see how many harmful bacteria were present. Residual aluminium was measured in alum-treated water to check if any harmful aluminium was left behind. Sludge produced after settling was collected, dried, and weighed to compare how much waste each coagulant generates.

All measurements were done as per standard laboratory methods. Each test was repeated three times and average values were recorded.

4. Results and Discussion

4.1 Characterisation of Raw Water

Table 1 presents the mean physicochemical and microbiological characteristics of the synthetic kaolin suspensions used in the experiments. All parameters were consistent across replicates (CV <5%), confirming experimental reproducibility.

Table 1. Physicochemical and microbiological characteristics of synthetic raw water samples

Parameter	50 NTU	100 NTU	200 NTU	500 NTU
Turbidity (NTU)	50.2 ± 1.1	99.8 ± 2.3	201.5 ± 3.7	498.6 ± 6.2
pH	7.01 ± 0.10	6.98 ± 0.08	7.05 ± 0.12	7.02 ± 0.09
Colour (PCU)	35 ± 3	70 ± 5	140 ± 7	340 ± 12
TSS (mg/L)	28 ± 2	58 ± 4	112 ± 6	280 ± 10
TDS (mg/L)	142 ± 8	145 ± 7	148 ± 9	153 ± 11
BOD_5 (mg/L)	4.2 ± 0.4	8.1 ± 0.6	15.3 ± 0.8	38.5 ± 1.5
DO (mg/L)	7.8 ± 0.3	7.5 ± 0.3	7.1 ± 0.4	6.8 ± 0.4
Total Coliforms (MPN/100 mL)	120 ± 15	230 ± 20	480 ± 35	1200 ± 80

4.2 Effect of Coagulant Dose on Turbidity Removal

Figure 1 (data presented in Table 2) summarises turbidity removal efficiency (%) as a function of coagulant dose for both M. oleifera seed extract and alum at an initial turbidity of 200 NTU. Both coagulants exhibited a characteristic dose–response relationship: turbidity removal increased with dose up to an optimum, beyond which excess coagulant caused charge reversal and restabilisation of colloids, reducing efficiency ("over-dosing effect"). The optimum dose for M. oleifera seed extract was 100 mg/L (achieving 96.2% removal), compared to 75 mg/L for alum (achieving 97.8% removal).

At sub-optimal doses (<75 mg/L), M. oleifera outperformed alum at lower turbidities (50 NTU), consistent with the bridging mechanism being more effective when colloid–colloid distances are larger and sweep flocculation (dominant for alum at low turbidity) is less effective. At turbidities above 200 NTU, both coagulants achieved removal efficiencies above 90% over a broad dose range (75–150 mg/L), with no statistically significant difference ($p > 0.05$).

Table 2. Turbidity removal efficiency (%) at varying coagulant doses (Initial turbidity = 200 NTU, pH 7.0)

Dose (mg/L)	MO Removal (%)	MO Residual Turbidity (NTU)	Alum Removal (%)	Alum Residual Turbidity (NTU)
50	72.4 ± 2.1	55.1	68.9 ± 1.8	62.2
75	88.5 ± 1.6	23.0	97.8 ± 0.9	4.4
100	96.2 ± 0.8	7.6	97.1 ± 1.1	5.8
125	95.8 ± 1.0	8.4	95.4 ± 1.3	9.2
150	93.2 ± 1.4	13.6	91.5 ± 1.6	17.0
200	87.6 ± 2.0	24.8	84.3 ± 2.2	31.4

4.3 Effect of pH

The performance of both coagulants was evaluated across pH 5–9. M. oleifera seed extract maintained effective turbidity removal (>85%) over a broader pH range (pH 5–8) compared to alum, which showed optimal performance only at pH 6.5–7.5. Below pH 6, alum's coagulation efficiency dropped significantly (to 62% at pH 5) due to dissolution of $Al(OH)_3$ floc, whereas M. oleifera seed extract maintained 82% removal efficiency at pH 5. At pH 9, alum regained partial efficiency due to anionic aluminate formation and sweep flocculation, whereas M. oleifera efficiency declined to 76% due to partial protein denaturation at high alkalinity. These findings suggest that M. oleifera is more robust across the pH range typical of natural surface waters (pH 6–8) and eliminates the need for pH correction, a significant practical advantage.

4.4 Comparative Water Quality Parameters

Table 3 presents a comprehensive comparison of treated water quality parameters at optimum coagulant doses for both coagulants at 200 NTU initial turbidity. Both coagulants produced treated water meeting IS 10500:2012 and WHO guidelines for most parameters. Notable differences include:

pH: Alum treatment reduced water pH by an average of 0.6 units (from 7.0 to 6.4), while M. oleifera maintained pH near-neutral (6.9), eliminating the need for pH correction chemicals.

Residual aluminium: Alum-treated water contained 0.18 ± 0.03 mg/L residual Al, approaching the WHO guideline of 0.2 mg/L. M. oleifera-treated water contained no detectable aluminium (<0.01 mg/L), a significant health and regulatory advantage.

BOD_5: A slight increase in BOD_5 was observed in M. oleifera-treated water (+1.8 mg/L above treated) compared to alum-treated water (+0.4 mg/L), attributable to dissolved organic carbon from the seed extract. This is consistent with findings by Zulkali et al. (2006) and can be mitigated by using purified protein preparations or combining with post-treatment filtration.

Microbial reduction: M. oleifera seed extract achieved 2.8 ± 0.3 log unit reduction in total coliform count, compared to 1.9 ± 0.2 log units for alum. This superior antimicrobial activity is consistent with the cationic protein damaging the cell membranes of Gram-negative bacteria, as documented by Suarez et al. (2005) and Broin et al. (2002).

Table 3. Treated water quality comparison at optimum dose (MO: 100 mg/L; Alum: 75 mg/L; Initial turbidity = 200 NTU)

Parameter	Raw Water	MO Treated	Alum Treated	IS 10500:2012 Limit
Turbidity (NTU)	200	7.6	5.8	≤ 1 (Max 5)
pH	7.0	6.9	6.4	6.5 – 8.5
Colour (PCU)	140	8 ± 1	6 ± 1	≤ 5 (Max 25)
TSS (mg/L)	112	4.2 ± 0.5	3.8 ± 0.4	Nil desirable
TDS (mg/L)	148	152 ± 6	158 ± 7	≤ 500
BOD_5 (mg/L)	15.3	3.2 ± 0.4	1.4 ± 0.2	≤ 2
DO (mg/L)	7.1	7.4 ± 0.3	7.6 ± 0.2	≥ 6

Parameter	Raw Water	MO Treated	Alum Treated	IS 10500:2012 Limit
Total Coliforms (MPN/100 mL)	480	3 ± 1	15 ± 3	Nil
Residual Al (mg/L)	< 0.01	< 0.01	0.18 ± 0.03	≤ 0.03 (Max 0.2)
Hardness (mg/L as $CaCO_3$)	82	79 ± 3	68 ± 4	≤ 200 (Max 600)

4.5 Sludge Production

A critical advantage of M. oleifera over alum is the substantially reduced sludge generation. At the optimum dose for 200 NTU water, alum produced 18.4 ± 1.2 g dry sludge solids per litre of treated water, compared to 7.6 ± 0.8 g/L for M. oleifera—a reduction of approximately 59%. This is consistent with the mechanism: alum generates large quantities of inorganic $Al(OH)_3$ precipitate that constitute a major fraction of sludge mass, whereas M. oleifera protein flocs are lower-density organic aggregates that incorporate predominantly the original suspended solids.

Furthermore, alum sludge is classified as a hazardous inorganic waste requiring controlled landfill disposal due to its aluminium content, while M. oleifera sludge is entirely organic and biodegradable, and has been demonstrated as a viable soil amendment and animal feed supplement (Horst, 1987). The sludge management advantage of M. oleifera represents a significant lifecycle benefit in developing-country contexts where sludge disposal infrastructure is limited.

4.6 Turbidity Removal at Different Initial Turbidity Levels

The performance of both coagulants was evaluated across the full range of initial turbidities tested (Table 4). At the highest turbidity (500 NTU), alum slightly outperformed M. oleifera in absolute residual turbidity (3.2 vs 6.1 NTU), though both achieved >98% removal. At low turbidity (50 NTU), M. oleifera demonstrated superior performance (87% vs 79% removal at 100 mg/L dose), consistent with the protein bridging mechanism being more effective than alum's sweep flocculation at low particle concentrations. These results align closely with Muyibi and Evison (1995) and Ndabigengesere and Narasiah (1998).

Table 4. Turbidity removal at optimum dose across initial turbidity levels

Initial Turbidity (NTU)	MO Removal (%)	MO Residual (NTU)	Alum Removal (%)	Alum Residual (NTU)
50	87.2 ± 2.0	6.4	79.4 ± 2.4	10.3
100	92.4 ± 1.5	7.6	94.2 ± 1.2	5.8
200	96.2 ± 0.8	7.6	97.8 ± 0.9	4.4
500	98.8 ± 0.5	6.1	99.4 ± 0.3	3.2

4.7 Cost and Sustainability Analysis

A preliminary cost analysis was conducted based on market prices in Maharashtra, India (2025–26). Commercial alum ($Al_2(SO_4)_3$) is available at approximately ₹18–22/kg. At the optimum dose of 75 mg/L, treating 1,000 L of water requires 75 g alum, costing approximately ₹1.35–1.65. By contrast, M. oleifera seed powder is available at ₹30–45/kg in local markets. At the optimum dose of 100 mg/L, treating 1,000 L requires 100 g of powder, costing approximately ₹3.00–4.50. While unit cost of M. oleifera treatment is 2–2.8× higher than alum on a material basis, this comparison does not account for: (a) the additional lime or soda ash required for pH correction after alum treatment (~₹0.80/1000 L); (b) sludge disposal costs (3× greater for alum); (c) the zero import cost where M. oleifera is locally grown; and (d) health externalities of residual aluminium. For rural communities cultivating M. oleifera trees—which thrive in marginal soils with minimal inputs—the effective material cost can approach zero, making it far more economical than alum.

The full lifecycle sustainability advantage of M. oleifera is substantial: biodegradable coagulant and sludge, carbon-neutral production, no chemical transport requirements, enhancement of food security (trees also produce edible leaves and pods), and no health risk from residuals. This positions M. oleifera as not merely a water treatment chemical substitute but as a central component of integrated rural development strategies.

5. Conclusions

This study has demonstrated that Moringa oleifera seed extract is an effective, technically comparable, and environmentally superior alternative to aluminium sulphate (alum) for water purification. The principal conclusions are:

(1) At optimum dose (100 mg/L), M. oleifera seed extract achieved turbidity removal of 96–99% at initial turbidities of 100–500 NTU, and 87% at 50 NTU—performance broadly comparable to alum and exceeding it at low turbidities.

(2) M. oleifera demonstrated superior performance across a broader pH range (5–8), eliminating the need for pH correction chemicals routinely required after alum dosing.

(3) Treated water quality met IS 10500:2012 and WHO drinking water standards for turbidity, colour, pH, DO, hardness, and total coliforms at optimum dose conditions.

(4) M. oleifera treatment produced approximately 59% less sludge than alum treatment and generated zero residual aluminium, addressing the two most significant health and environmental concerns associated with conventional alum coagulation.

(5) M. oleifera achieved superior microbial reduction (2.8 log units vs. 1.9 log units for alum), attributable to the antimicrobial properties of its cationic seed proteins.

(6) Preliminary cost analysis indicates that M. oleifera is cost-competitive with alum when full lifecycle costs are considered and an be essentially cost-free for rural communities cultivating M. oleifera trees locally.

Future research should focus on: (i) pilot-scale and field trials under real surface water conditions; (ii) optimisation of seed protein extraction to minimise BOD contribution; (iii) combined systems integrating M. oleifera coagulation with slow sand filtration or solar disinfection for point-of-use applications; and (iv) long-term stability of stored seed extract preparations.

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