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# *Opuntia ficus-indica* (L.) as a natural coagulant and alum aid for surface water clarification in tropical Uganda

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## ABSTRACT

Plant-based coagulants could reduce reliance on traditional chemicals for water clarification; however, their performance requires validation using actual, very turbid waters. This study assessed the efficacy of *Opuntia ficus-indica* (L.) extract, aluminium sulphate (alum), and a 1:1 *Opuntia*–alum formulation for the clarity of raw water in Uganda through jar tests, varying coagulant concentrations from 10 to 60 mg/L and specific pH conditions. Untreated water had a turbidity of 135 ± 5 NTU and a colour measurement of 884 ± 8 Pt–Co units. *Opuntia* eliminated 54–82% of turbidity and 56–76% of colour, while alum removed 78–83% and 76–89%, respectively. The hybrid formulation had the highest observed removals, attaining 96% for turbidity at 30 mg/L and 95% for colour at 60 mg/L. Nonetheless, trends in pH, alkalinity, and conductivity indicated that treatment chemistry was responsive to dosage and the alkaline extraction method. The findings offer region-specific evidence that *Opuntia* can serve as a coagulant aid for heavily contaminated tropical surface water. The study did not assess post-treatment microbial elimination, sludge characteristics, lifecycle effects, or full-scale expenses; hence, findings are restricted to clarifying efficacy and laboratory-scale operational behaviour.

**Key words:** aluminium sulphate, colour removal, natural coagulant, *Opuntia ficus-indica* (L), surface-water clarification

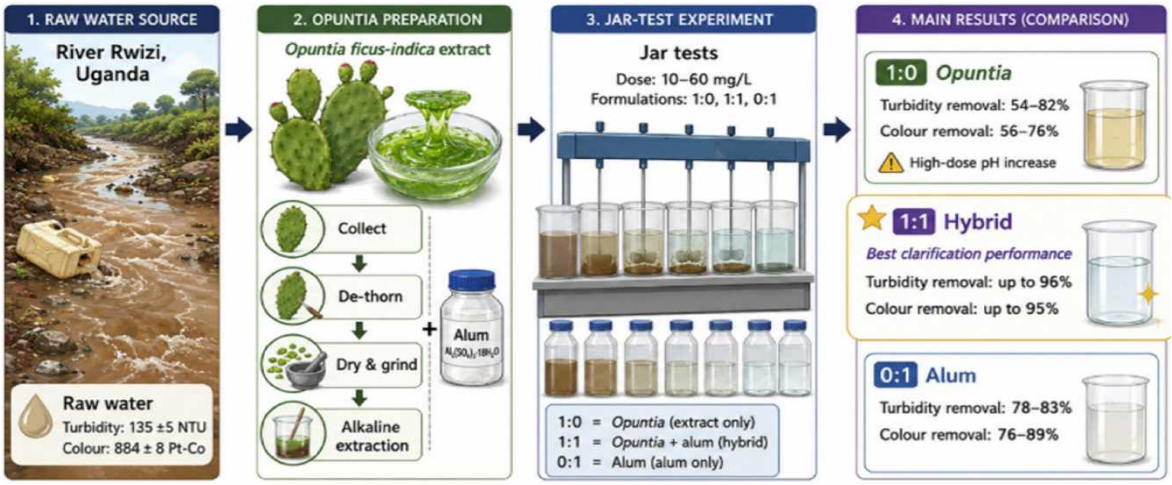
## HIGHLIGHTS

- *Opuntia ficus-indica* (L.) was evaluated as a natural coagulant for treating surface water in Uganda.
- Hybrid coagulation using *Opuntia* and alum achieved up to 96% turbidity and 95% colour removal.
- The hybrid formulation produced the highest observed clarification performance across the tested doses.
- The findings support further pilot-scale evaluation of *Opuntia* as an alum coagulant aid.

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## GRAPHICAL ABSTRACT




## 1. INTRODUCTION

The production of safe drinking water continues to be challenging in numerous low- and middle-income countries, where surface water sources are compromised by erosion, wastewater discharge, and catchment disruption. Such inputs elevate suspended particles, colour, and natural organic matter, thus augmenting the requirement for coagulation and subsequent treatment (Abujazar *et al.* 2022; Lwasa *et al.* 2024). The difficulty is particularly significant in rapidly expanding towns, where treatment facilities must adapt to fluctuating raw water quality while managing chemical usage and operational expenses.

Aluminium sulphate is extensively utilised due to its ability to destabilise colloids and facilitate the development of aluminium hydroxide flocs. Its efficacy, however, is significantly influenced by pH and alkalinity, and its hydrolysis depletes alkalinity (Matilainen *et al.* 2010). The operational constraints have stimulated research on locally available biodegradable plant-derived coagulants that may serve as primary coagulants or coagulant aids (Koul *et al.* 2022).

The mucilage of *Opuntia ficus-indica* (L.) comprises polysaccharides with carboxyl and hydroxyl functional groups, which facilitate particle removal by adsorption and interparticle bridging (Otálora *et al.* 2022b; Benalia *et al.* 2024). Prior research has indicated significant turbidity and colour reduction using *Opuntia*-based products; however, efficacy is influenced by extraction techniques, raw water composition, dosage, and pH (Gandiwa *et al.* 2020). The integration of a traditional coagulant in hybrid treatment may enhance process robustness.

Evidence regarding severely polluted tropical seas in Sub-Saharan Africa is still scarce (Alazaiza *et al.* 2022; Lwasa *et al.* 2024). Comparative data acquired under uniform jar test circumstances are essential to differentiate the clarifying efficacy of *Opuntia* alone, alum alone, and their combination. Assertions on disinfection, sludge reduction, and sustainability necessitate direct measurements and should not be reduced just to turbidity removal.

This study assessed *O. ficus-indica* (L.) extract as a natural coagulant and alum adjunct for River Rwizi water in South Western Uganda. The objectives were to (i) characterise the raw water; (ii) assess the effects of *Opuntia*, alum, and a 1:1 hybrid formulation on pH, alkalinity, electrical conductivity (EC), turbidity, and colour; and (iii) discover the dose and pH conditions correlated with optimal clarifying performance. The presented tests did not encompass microbial eradication, sludge characteristics, lifecycle implications, or full-scale economics.

## 2. MATERIALS AND METHODS

### 2.1. Raw water source and characterisation

Untreated water was sourced from the Rwizi River in southeastern Uganda. The river emanates from the Buhweju highlands and provides water to homes and industrial consumers in locales like Sanga, Bwizibwera, and Mbarara City. Samples were collected and processed following the Standard Methods for the Examination of Water and Wastewater (APHA 2023).

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Raw water characterisation including temperature, apparent colour, pH, turbidity, EC, total dissolved solids (TDS), total suspended solids (TSS), and *Escherichia coli*. Calibrated probes were employed for pH and EC measurements, turbidity was assessed nephelometrically, colour and TSS were quantified spectrophotometrically, and *E. coli* was enumerated via membrane filtration utilising chromogenic medium. *Escherichia coli* was assessed just in untreated water; microbial elimination during treatment was not examined.

### 2.2. Extraction of coagulant from cactus *Opuntia*

Fresh *O. ficus-indica* (L.) cladodes were harvested from wild plants located along the Mbarara–Kabale highway in Southeastern Uganda. Thorns were excised, and the cladodes were rinsed with distilled water. The material was air-dried for 2 weeks and then ground and sieved using a 0.35 mm sieve. The resultant powder was preserved in polyethene bags within a desiccator at ambient temperature. Fifty grams of *Opuntia* powder were combined with 0.05 M sodium hydroxide to enhance extraction and solubilise active ingredients, adhering to the specified extraction protocol. The suspension was agitated at 700 rpm for 20 min, permitted to settle for 30 min, and subsequently filtered using 8 μm filter paper. The filtrate was preserved at 4 °C before use. The use of sodium hydroxide during extraction may affect the pH, alkalinity, and conductivity of the treated water; these effects should be evaluated with caution. A stock solution of analytical grade aluminium sulphate was made independently.

### 2.3. Jar test procedure

Three formulas were evaluated: *Opuntia* solely (1:0), a blend of *Opuntia* and alum (1:1), and alum exclusively (0:1). One litre of raw water was allocated to each jar, and total coagulant dosages of 10, 20, 30, 40, 50, and 60 mg/L were assessed. For each experimental trial, 1,000 mL of untreated water was deposited into a clean beaker and positioned in a jar test device. The necessary dosage was introduced to the raw water, followed by quick mixing at 125 rpm for 2 min to guarantee uniform distribution of the coagulant. Subsequently, steady mixing at 70 rpm was conducted for 30 min to facilitate floc development and aggregation. After flocculation, the samples were permitted to settle undisturbed for 30 min. The cleared supernatant was subsequently extracted from the upper section of each beaker for water quality assessment.

Each treatment condition was performed in triplicate ($n = 3$) to enhance reproducibility and facilitate statistical analysis. Consequently, for each dosage and coagulant formulation, three distinct beakers were made and evaluated independently. The assessed metrics post-treatment comprised pH, turbidity, colour, EC, and total alkalinity. The efficiencies for turbidity and colour reductions are determined using Equation (1):

$$\text{Removal efficiency (\%)} = \frac{[C_0 - C_t]}{C_0} \times 100 \quad (1)$$

where $C_0$ represents the untreated water value and $C_t$ denotes the value post-treatment. Results are presented as observed values and removal percentages.

### 2.4. Statistical analysis

Each experiment was carried out in three separate repetitions ($n = 3$). The data were reported as mean ± standard deviation. Two-way analysis of variance (ANOVA) was used for the dosage trials to assess the effects of coagulant formulation, dose, and their combination on pH, total alkalinity, EC, turbidity removal, and colour removal. There were six dosage levels, ranging from 10 to 60 mg/L, and three coagulant formulation levels: *Opuntia* alone (1:0), *Opuntia*–alum mixture (1:1), and alum alone (0:1).

A separate two-way ANOVA was used for the pH trials to assess the effects of formulation, initial pH, and their interaction. Tukey's honestly significant difference test was used for paired comparisons in cases where significant effects were found. The Shapiro–Wilk test was used to determine whether the model residuals were normal, and Levene's test was used to determine whether the variance was homogeneous. The threshold for statistical significance was set at $p < 0.05$.

Python was used to fit second-order polynomial models to the dosage-pH data for the response-surface study. Python was used for data processing and model fitting. ANOVA, the coefficient of determination ($R^2$), model ($F$)-value, and the significance of linear interaction and quadratic factors were used to evaluate the model's adequacy.

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## 3. RESULTS AND DISCUSSION

This section presents and discusses the performance of *O. ficus-indica* (L.) (bio-coagulant), aluminium sulphate (alum), and their combined formulations in the treatment of turbid surface water. Experimental results are evaluated in terms of pH, alkalinity, EC, turbidity, and colour removal efficiencies, as well as the relationship between turbidity and pH, as functions of coagulant dosage. Throughout this section, the coagulant ratios are denoted as 1:0 for bio-coagulant only (*O. ficus-indica* (L.)), 1:1 for the bio-coagulant–alum hybrid combination, and 0:1 for alum only. The observed trends are interpreted based on coagulation–flocculation mechanisms and critically compared with findings from related studies, with particular emphasis on tropical water treatment contexts.

### 3.1. Characteristics of raw water from river Rwizi

Table 1 displays the average physicochemical and microbiological characteristics of raw water from River Rwizi, compared with the WHO drinking water requirements. The untreated water from Rwizi is highly polluted and requires comprehensive filtration before it can be considered safe for human consumption. The turbidity and colour values greatly exceeded the WHO-recommended level, highlighting the abundance of suspended particles and natural organic matter. This can be ascribed to wastewater discharges, soil erosion, and surface runoff within the watershed (Edzwald 2012). The EC and TDS of the raw water adhered to WHO-approved norms, indicating low salinity and minimal dissolved inorganic pollution. The raw water pH exceeded the WHO-recommended range, potentially impacting coagulation efficacy and disinfection effectiveness. *Escherichia coli* levels were markedly higher compared with the WHO limit of 0 CFU/100 mL, signifying severe faecal contamination (WHO 2017).

**Table 1** | Raw water characteristics

| Parameter | Units | Mean ± STD | WHO standards/operational |
|---|---|---|---|
| Turbidity | NTU | 135 ± 5 | ≤5 |
| Colour | Pt–Co | 884 ± 8 | ≤15 |
| E.C | μS/cm | 220 ± 12 | ≤1,500 |
| TDS | mg/l | 68 ± 4 | ≤1,000 |
| Temperature | °C | 26 ± 1 | |
| pH | | 8.6 ± 0.5 | 6.5–8.5 |
| TSS | mg/l | 166 ± 7 | ≤25 |
| *E. coli* | CFU/100 ml | 6,000 ± 150 | 0 |

### 3.2. Effect of coagulant dosage on the pH

Figure 1 shows the influence of coagulant dosage on the pH of treated water for *O. ficus-indica* (L.) alone (1:0), *O. ficus-indica* (L.)–alum mixture (1:1), and alum alone (0:1). Data dots denote mean values derived from three separate replication experiments, while error bars indicate ±1 standard deviation.

An overall elevation in pH was noted with escalating coagulant dosage across all formulations. The pH for *Opuntia* rose from 6.33 ± 0.29 at 10 mg/L to 10.50 ± 0.50 at 60 mg/L. The *Opuntia*–alum combo showed a steadier increase, ascending from 5.17 ± 0.58 to 8.50 ± 0.50 within the identical dosage range. The increase could be linked to the *Opuntia*-containing therapies, which are likely affected by the 0.05 M sodium hydroxide employed in the extraction process. In contrast, alum hydrolysis often generates acidity and depletes alkalinity; thus, the rising pH trend associated with alum alone should be regarded as a characteristic of the observed dataset that necessitates validation by repeated measurements and quality control records of the instruments. Conversely, alum alone elevated the pH from 3.67 ± 0.58 at 10 mg/L to 9.50 ± 0.50 at 60 mg/L. Two-way ANOVA indicated that pH was significantly affected by both coagulant formulation ($F$ (2,36) = 92.91, $p < 0.001$) and dosage ($F$ (5,36) = 181.98, $p < 0.001$). A substantial interaction effect between formulation and dose was observed ($F$ (10,36) = 7.23, $p < 0.001$), signifying that the extent of pH alteration with increasing dosage was contingent upon the coagulant formulation employed. The *Opuntia*–alum hybrid often yielded intermediate pH values, sustaining pH within a moderate range of roughly 6.0–7.7 at dosages of 20–50 mg/L.

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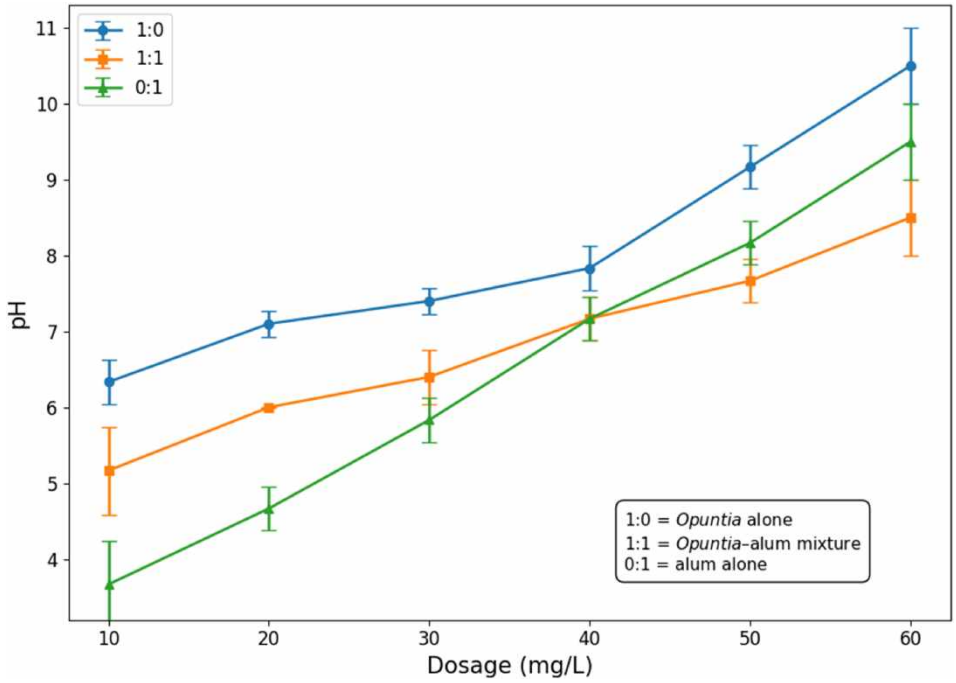



**Figure 1** | Coagulant dosage versus pH.

The above data suggest a wider usable pH range for the hybrid formulation; nevertheless, they do not confirm regulatory compliance, as downstream filtration and disinfection were not evaluated. *Opuntia* mucilage has galacturonic acid residues and calcium-binding polysaccharides that increase pH by hydroxyl ion release, while alum hydrolysis produces sulphuric acid, especially at lower quantities (Van Rooyen *et al.* 2024). A recent study by Megersa *et al.* similarly reported pH elevations upon the application of *O. ficus-indica* (L.) for the treatment of turbid water, ascribed to the polyelectrolyte characteristics of the mucilage (Megersa *et al.* 2024).

Furthermore, the data indicate that pure *Opuntia* at concentrations over 30 mg/L repeatedly exceeded this threshold, attaining potentially concerning alkalinity levels. In contrast, the 1:1 combination exhibited enhanced pH regulation, sustaining values within tolerable limits at dosages of 20–50 mg/L without necessitating post-treatment modifications. The buffering capacity provides a notable practical benefit, as highlighted by Tijjani Usman and others, who underscored that pH management is a crucial challenge in the application of plant-based coagulants in resource-constrained tropical environments (Tijjani Usman *et al.* 2023). The synergistic impact noted in the hybrid formulation indicates that the amalgamation of natural and chemical coagulants may be an efficient approach for attaining both treatment efficacy and water quality compliance.

### 3.3. Effect of coagulant dosage on total alkalinity

Figure 2 shows the impact of coagulant dosage on total alkalinity for *Opuntia* only (1:0), the *Opuntia*–alum combination (1:1), and alum solely (0:1). Data points indicate mean values, while error bars denote ±1 standard deviation from three independent repeat experiments.

Results for total alkalinity fluctuated based on the coagulant composition and dosage. The total alkalinity for *Opuntia* rose from 143.33 ± 7.64 mg/L as $CaCO_3$ at 10 mg/L to 178.33 ± 2.89 mg/L as $CaCO_3$ at 60 mg/L. The *Opuntia*–alum mixture elevated from 149.33 ± 2.08 to 179.33 ± 2.31 mg/L as $CaCO_3$ within the identical dose range. Alum alone yielded relatively low alkalinity readings, ranging from 139.33 ± 1.53 to 160.00 ± 2.00 mg/L as $CaCO_3$, thereafter decreasing to 153.00 ± 1.00 mg/L at a concentration of 50 mg/L. Total alkalinity rose with dosage for *Opuntia* alone and the combination formulation. This pattern aligns with the transfer of alkalinity from the sodium hydroxide extraction phase. However, the alum-only series rose, which contradicts the anticipated alkalinity consumption during alum hydrolysis. The *Opuntia* powder was extracted with 0.05 M sodium hydroxide, and the remaining hydroxide ions in the filtered extract may have directly enhanced the acid-neutralising ability of the treated water. Two-way ANOVA indicated that total alkalinity was significantly influenced by

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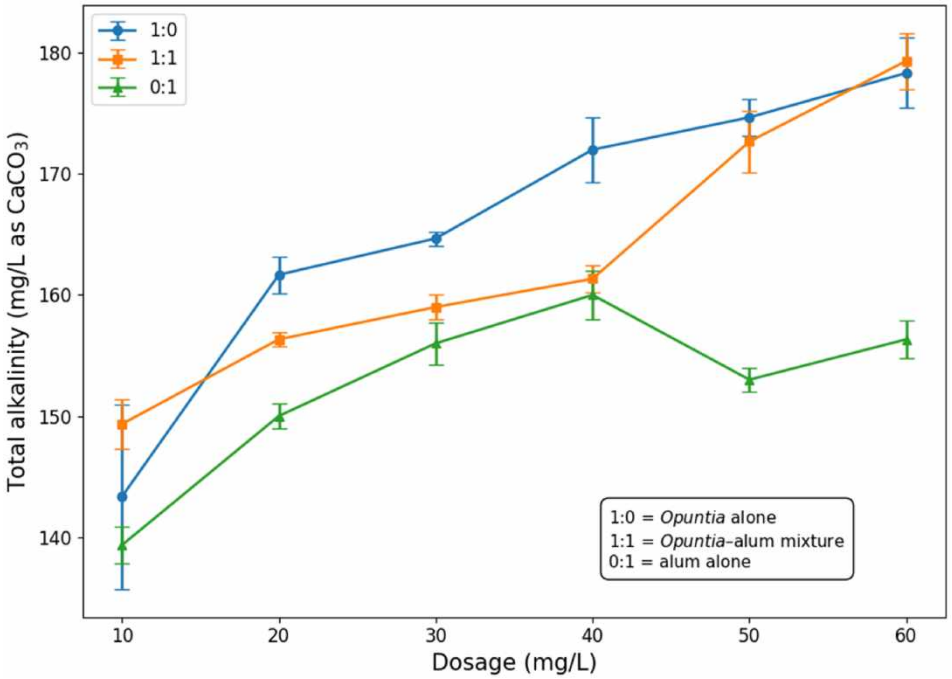



**Figure 2** | Coagulant dosage versus Total Alkalinity.

coagulant formulation ($F$ (2,36) = 144.44, $p < 0.001$) and dosage ($F$ (5,36) = 135.77, $p < 0.001$). A notable formulation × dose interaction was identified ($F$ (10,36) = 13.38, $p < 0.001$), demonstrating that the total alkalinity response to increasing dosage was contingent upon the coagulant formulation.

These findings correspond with observations from investigations on plant-based coagulants, where natural formulations, such as cactus extracts, have shown dose-dependent effects on water alkalinity and other physicochemical characteristics. Gandiwa *et al.* (2020) documented alterations in total alkalinity and pH while employing *Opuntia* and *Moringa* coagulants, both individually and in combination with alum, underscoring the impact of plant coagulants on water chemistry. Analyses of plant-based coagulants emphasise that dose-dependent variations in alkalinity and pH frequently pose issues in tropical water treatment systems utilising natural coagulants (Tijjani Usman *et al.* 2023).

### 3.4. Effect of coagulant dosage on electrical conductivity

Figure 3 shows the impact of coagulant dosage on EC for *Opuntia* only (1:0), the *Opuntia*–alum combination (1:1), and alum exclusively (0:1). Data points denote mean values, while error bars indicate ±1 standard deviation from three independent replication experiments.

EC varied significantly among the three coagulant formulations, with values expressed as mean ± standard deviation from three separate repetitions. For *Opuntia*, conductivity continuously diminished with escalating dosage, decreasing from 205.67 ± 0.58 μS/cm at 10 mg/L to 217.00 ± 1.00 μS/cm at 60 mg/L. The *Opuntia*–alum mixture showed a marginal rise from 191.67 ± 2.08 μS/cm at 10 mg/L to 215.33 ± 3.79 μS/cm at 60 mg/L. Alum alone yielded the lowest conductivity results, demonstrating a progressive increase from 155.33 ± 1.53 to 166.33 ± 3.79 μS/cm within the same dosage range. Two-way ANOVA indicated that EC was significantly influenced by coagulant formulation ($F$ (2,36) = 3,389.74, $p < 0.001$) and dosage ($F$ (5,36) = 74.69, $p < 0.001$). A notable formulation × dose interaction was identified ($F$ (10,36) = 5.05, $p < 0.001$), demonstrating that the extent of conductivity enhancement with dosage varied across the three formulations.

The findings are consistent with previous studies, which reported conductivity increases following the application of plant-based coagulants, attributed to ionic species released from the biopolymer matrix (Gandiwa *et al.* 2020). The elevated conductivity noted in the treatments containing *Opuntia* may partially result from ionic species introduced by the 0.05 M sodium hydroxide utilised during extraction. The rising conductivity in the alum-only treatment aligns with the introduction of dissolved ionic species, specifically sulphate, from aluminium sulphate.

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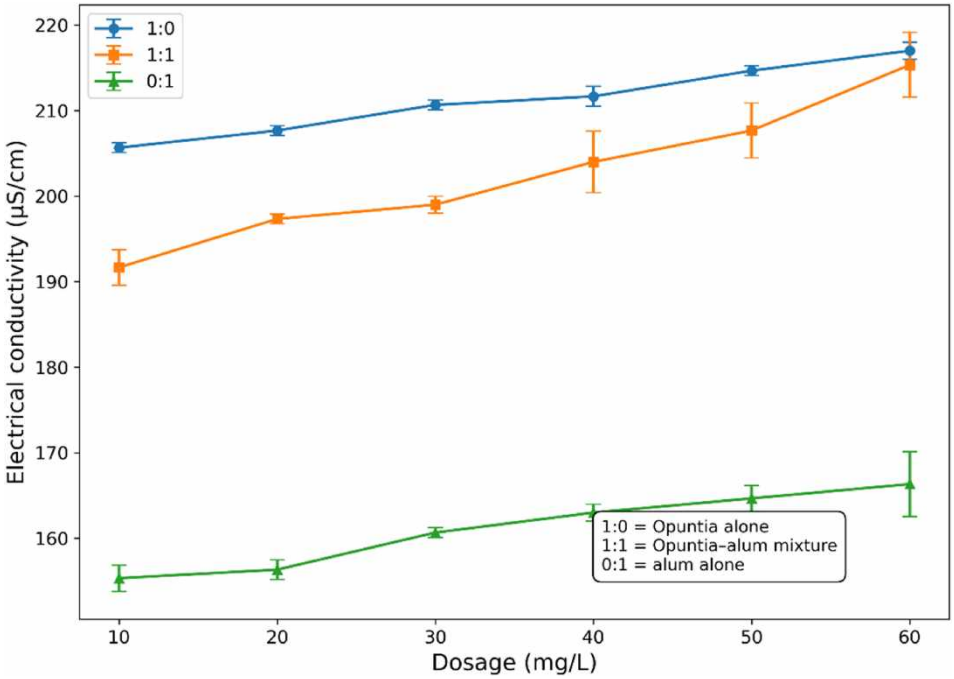



**Figure 3** | Electrical conductivity against coagulant dosage.

### 3.5. Effect of coagulant dosage on turbidity removal efficiency

Figure 4 assesses the impact of coagulant dosage on turbidity removal efficiency for the various treatment formulations.

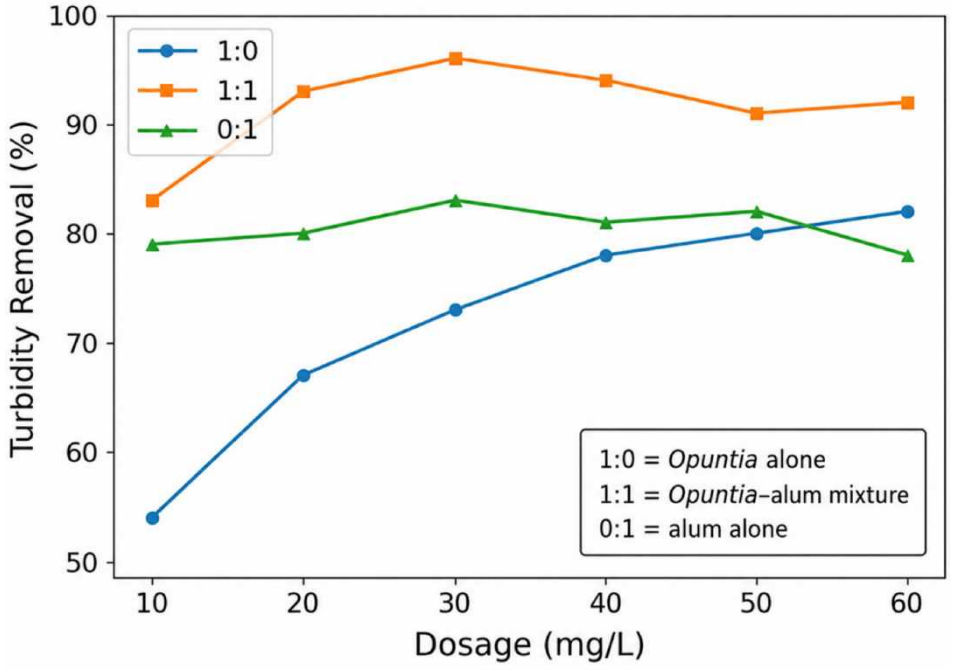



**Figure 4** | Turbidity removal versus coagulant.

The efficacy of turbidity removal significantly differed across the three coagulant formulations, with the hybrid treatment (1:1) exhibiting higher performance across the whole dosage spectrum. The *Opuntia*–Alum combination attained a maximum clearance rate of 96% at 30 mg/L, sustaining an efficiency of 91% across all tested dosages. Pure *Opuntia* extract (1:0) demonstrated a gradual enhancement from 54% at 10 mg/L to

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82% at 60 mg/L, whereas pure aluminium sulphate (0:1) displayed a reasonably consistent efficacy ranging from 78 to 83%, with optimum elimination at 30 mg/L.

The results correspond with the findings of Otálora and fellow researchers (2022a), who documented turbidity removal efficiencies reaching 94% with *O. ficus-indica* in conjunction with iron (III) chloride, crediting the improved performance to synergistic bridging mechanisms that facilitated the enhancement of chemical floc formation by cactus polysaccharides. Nonetheless, the efficacy of pure *Opuntia* (54–82%) in this study markedly lagged previous research, which reported turbidity reductions of 85–93% using solitary *O. ficus-indica* (L.) extracts under controlled settings. Ali and co-researchers (2025) reported elevated efficiencies in synthetic and natural waters. This disagreement presumably arises from variations in raw water features, specifically the intricate mix of organic matter in River Rwizi compared with controlled laboratory circumstances, which may have obstructed mucilage adsorption sites and diminished coagulation efficacy.

For treated water, the WHO sets a turbidity criterion of less than 5 NTU, with values below 1 NTU being ideal for disinfection. At a concentration of 30 mg/L, the hybrid formulation achieved a clearance rate of 91–96%, indicating substantial compliance potential. On the other hand, alum by itself only removed 78–83%, which is consistent with the findings of Husen *et al.* (2024), who found that alum efficacy was lower in streams that were rich in organic matter. According to recent research, *Opuntia* mucilage enhances floc formation through bridging; in both controlled and natural settings, Choudhary *et al.* and Amin *et al.* reported an 85% improvement in removal efficiency (Choudhary *et al.* 2019; Amin *et al.* 2025). This synergy explains the 1:1 blend's increased effectiveness by combining *Opuntia's* polymer bridging with alum's charge neutralisation to produce larger, quickly settling flocs.

### 3.6. Effect of coagulant dosage on colour removal efficiency

Figure 5 presents the influence of coagulant dosage on colour removal across the treatment formulations.

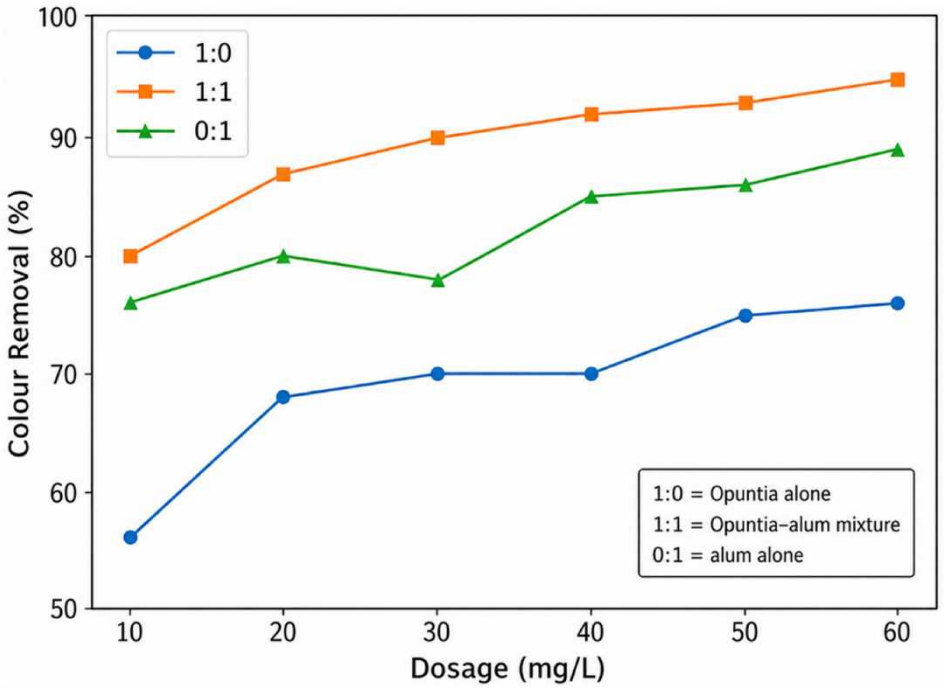



**Figure 5** | Colour removal versus coagulant dosage.

The efficacy of colour removal showed gradual enhancement with escalating dosage across all formulations. The hybrid therapy (1:1) demonstrated enhanced efficacy, varying from 80% at 10 mg/L to 95% at 60 mg/L, with optimal elimination observed at elevated dosages. Pure *Opuntia* extract (1:0) demonstrated moderate efficacy (56–76%), while pure aluminium sulphate (0:1) displayed intermediate efficacy (76–89%). These findings correspond with other research indicating a colour removal efficiency of 71.8% when utilising *O. ficus-indica* (L.) fruit peel mucilage for synthetic turbid water (Otálora *et al.* 2022b), ascribing the improved performance to

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the mucilage polysaccharides' capacity to complex with organic chromophores via adsorption and electrostatic interactions.

However, the performance of pure *Opuntia* in this investigation exhibited significant heterogeneity when contrasted with controlled laboratory trials. Ahmad *et al.* (2024) established that the effectiveness of natural coagulants diminishes markedly with elevated dissolved organic carbon (DOC) levels, attributable to the saturation of available binding sites. This phenomenon aligns with the substantial organic matter load in River Rwizi, which likely constrains the adsorption capacity of mucilage polysaccharides and diminishes colour removal efficiency.

The WHO advises a colour limit of 15 TCU for aesthetic acceptability in drinking water; however, there is no health-based recommendation. The hybrid formulation's continuously elevated removal rates (≥90% at dosages over 30 mg/L) indicate significant compliance potential, especially when colour removal is associated with the reduction of dissolved organic matter, essential for efficient disinfection. The exceptional efficacy of the 1:1 combination illustrates complementary mechanisms, wherein alum destabilises colloidal colour particles, while *Opuntia* polysaccharides promote floc aggregation and organic matter adsorption.

### 3.7. Effect of turbidity removal as a function of pH

Figure 6 explores how turbidity removal varied with changes in pH across the treatment formulations.

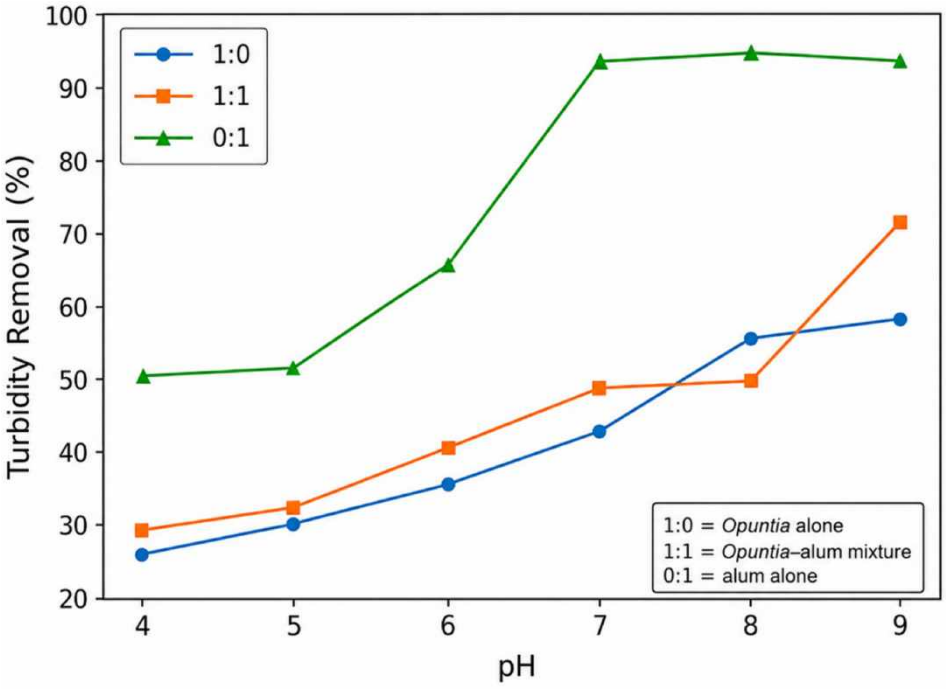



**Figure 6** | Turbidity removal as a function of pH.

The efficacy of turbidity reduction showed a significant dependence on pH across all coagulant formulations. Pure aluminium sulphate (0:1) exhibited peak efficacy at pH 7–8, attaining a clearance rate of 93–94%, with a significant reduction in performance under acidic conditions (50–51% at pH 4–5) and a little decrease in efficiency at alkaline settings (93% at pH 9). The hybrid formulation (1:1) showed moderate pH sensitivity, with removal rates varying from 29% at pH 4 to 71% at pH 9, whereas the pure *Opuntia* extract (1:0) displayed comparatively inferior performance throughout the pH range (26–58%), achieving peak efficiency at pH 9. These findings correspond with the established alum coagulation theory, wherein optimal efficacy is achieved around neutral pH, facilitating advantageous aluminium hydroxide precipitation and charge neutralisation conditions.

Alum exhibited peak efficacy at near-neutral pH (7–8), aligning with Krupińska (2023), who noted analogous pH optima for aluminium-based coagulants in surface waters. Nonetheless, the hybrid formulation's inadequate performance diverges from the results reported by Otálora *et al.*, who observed turbidity removal rates

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of 85–94% with *Opuntia*–chemical coagulant combinations within pH 6–8 (Otálora *et al.* 2022b), crediting the efficacy to synergistic mechanisms that maintained performance stability across wider pH ranges.

The unanticipated subpar efficacy of *Opuntia*-containing formulations at neutral pH (35–48% at pH 6–7) likely indicates interference from the chemistry of River Rwizi, including elevated levels of dissolved organic matter or competing ions that hinder mucilage adsorption. This is significant as dose experiments demonstrated optimal hybrid performance at 20–50 mg/L within the same pH range (6.5–8.0), whereas pH-based trials revealed reduced efficiency (40–49%). The discrepancy indicates that the composition of raw water and experimental conditions significantly affect coagulant behaviour. These findings underscore the importance of pH regulation when utilising natural coagulants in tropical waters characterised by complex chemical matrices.

### 3.8. Combined effects of dosage and pH on turbidity removal

Figure 7 illustrates the synergistic effects of coagulant dosage and starting pH on turbidity reduction by *Opuntia* only (1:0), the *Opuntia*–alum amalgamation (1:1), and alum solely (0:1). The response surfaces indicate that clarity performance was affected by both dosage and pH; the extent and pattern of the reaction varied among the formulations. The dosage dictates the amount of active coagulant accessible for particle destabilisation and floc formation, whereas pH influences coagulant speciation, particle surface charge, and the ionisation of active functional groups in plant-derived coagulants (Feng *et al.* 2015; Otálora *et al.* 2022a).

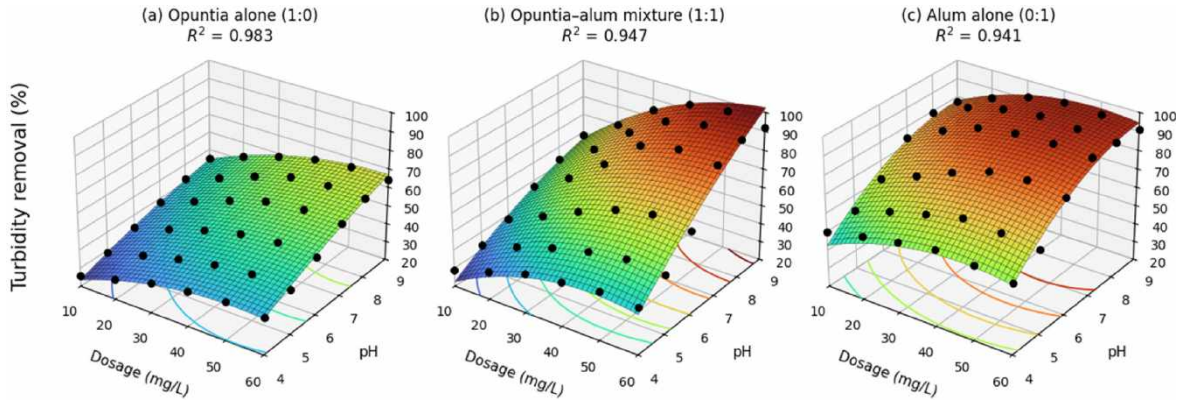



**Figure 7** | Combined effects of dosage and pH on turbidity.

*Opuntia* demonstrated a progressive enhancement in turbidity removal as dosage and pH increased. Removal efficiency varied from 26 to 41% at pH 4, with a peak of 65% at pH 9 with a dose of 50 mg/L. The enhanced performance under alkaline circumstances is probably due to the deprotonation of hydroxyl and carboxyl groups in *Opuntia* mucilage, which improves adsorption and interparticle bridging mechanisms (Otálora *et al.* 2022a). A minor decrease beyond the optimal dosage indicates potential saturation of adsorption sites or diminished bridging efficacy, a phenomenon frequently observed with plant-derived coagulants (Hadadi *et al.* 2022). Notwithstanding its efficacy, *Opuntia* alone attained lower removal efficiencies compared with the other therapies.

The *Opuntia*–alum combination had the most superior overall performance. Turbidity elimination significantly improved with increasing dosage and pH, with a peak of 96% at pH 8 and a concentration of 50 mg/L. The improved efficiency is due to the synergistic effect of alum and *Opuntia* polysaccharides. Alum facilitates charge neutralisation and sweeps flocculation via hydrolysed aluminium species, whereas *Opuntia* enhances adsorption and bridging processes, leading to the formation of bigger and more settleable flocs (Amin *et al.* 2025). The optimal performance noted between pH 7 and 8 aligns with advantageous aluminium hydrolysis and efficient polymer activity (Feng *et al.* 2015). The minor decrease in removal at 50 mg/L may suggest charge reversal, particle restabilisation, or residual polymer in solution (Otálora *et al.* 2022a).

Alum alone attained significant turbidity removal efficiency, reaching a maximum of 95% at pH levels of 7–8 and doses of 40–50 mg/L. The performance was significantly affected by pH, as the hydrolysis products of aluminium fluctuate with pH and dictate the prevailing coagulation mechanisms (Feng *et al.* 2015). The ideal pH range of 7–8 indicates efficient production of aluminium hydroxide flocs and sweep coagulation. At reduced pH

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levels or high dosages, unfavourable aluminium species, charge reversal, or particle restabilisation may diminish therapeutic efficacy (Otálora *et al.* 2022a).

The *Opuntia*–alum mixture surpassed both individual coagulants, attaining the highest turbidity reduction at 96%, followed closely by alum alone at 95%, while *Opuntia* alone achieved a maximum of 65%. The results suggest that the combination of *Opuntia* and alum can improve coagulation efficacy via synergistic mechanisms. The findings indicate that optimal clarity was achieved at mid to high levels, rather than at the highest dosage evaluated.

### 3.9. Combined effects of dosage and pH on colour removal

Figure 8 shows that the removal of colour was significantly affected by coagulant dosage and starting pH, exhibiting distinct reaction patterns for *Opuntia* alone (1:0), the *Opuntia*–alum mixture (1:1), and alum alone (0:1). Overall, elevated dosage and enhanced colour removal; however, excessive dosages sometimes led to diminished efficacy, suggesting potential overdosing effects. Comparable tendencies have been seen for both natural and inorganic coagulants, wherein dosage impacts particle destabilisation and flocculation, while pH affects coagulant efficacy and adsorption processes (Otálora *et al.* 2022a).

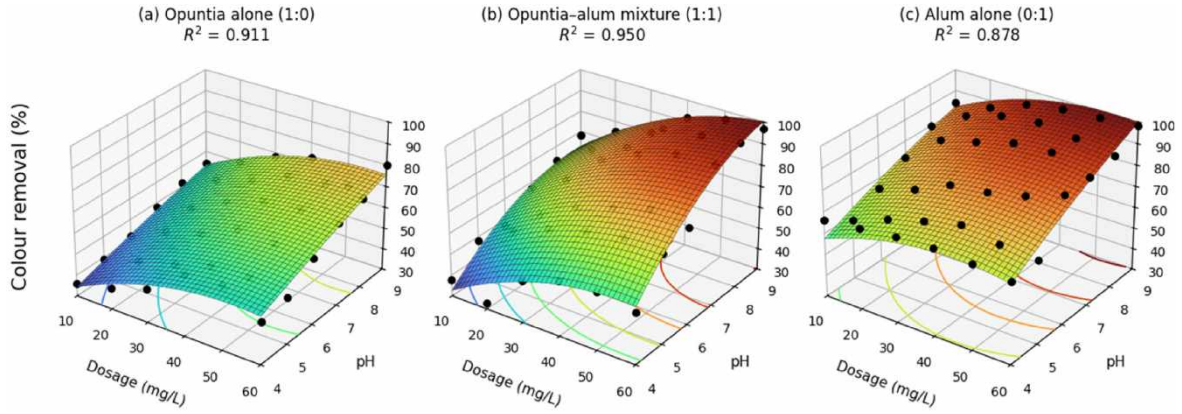



**Figure 8** | Combined effect of dosage and pH on colour removal.

Among the treatments, *Opuntia* exhibited the lowest colour removal efficiency, ranging from 36 to 52% at low dosages, with a peak of 80% at pH 9 and 60 mg/L. Greater performance at elevated pH levels may be ascribed to increased ionisation of polysaccharide functional groups, facilitating adsorption and polymer bridging. Minor reductions may be attributed to coagulant overdosing (Ji *et al.* 2024).

The *Opuntia*–alum combination demonstrated significantly enhanced colour removal, achieving 98% at pH 8 and 60 mg/L. Removal efficiencies over 94% were regularly attained within the pH range of 7–9 at doses of 40–60 mg/L. The enhanced efficacy of the hybrid formulation is probably attributable to the synergistic effects of aluminium-based charge neutralisation and sweep flocculation, along with the adsorption and bridging characteristics of *Opuntia* mucilage (Otálora *et al.* 2022a). The application of a 0.05 M NaOH extract may have affected therapeutic efficacy by altering the ionisation of cactus polymers and the chemistry of water (Benalia *et al.* 2026).

Alum alone exhibited remarkable colour removal, with up to 98% removal at pH 9 and a concentration of 60 mg/L. High efficiencies were sustained across an extensive pH range, especially between pH 7 and 9, owing to the generation of hydrolysed aluminium species that facilitate charge neutralisation, adsorption, and sweep flocculation. Minor reductions at elevated dosages indicate potential particle restabilisation due to surplus coagulant (Otálora *et al.* 2022a).

The combination of *Opuntia* and alum, as well as alum alone, resulted in the highest colour removals at 98%, while *Opuntia* alone reached a maximum of 80%. These findings underscore the necessity of optimising both pH and dose to enhance therapeutic efficacy.

## 4. CONCLUSION

This study demonstrates that Cactus *Opuntia* can substantially improve cleaner and more sustainable drinking water treatment systems in tropical regions. The cactus *Opuntia* exhibited notable coagulation and microbial

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reduction properties; however, its practical application was constrained by pH instability and narrower operational ranges at higher dosages. Conventional alum treatment, although effective, has demonstrated reduced efficacy in organic-rich surface water and is associated with heightened chemical demands and sustainability concerns.

The hybrid *Opuntia*–alum approach demonstrated the most balanced and robust performance, combining high efficiency in turbidity and colour removal with improved pH management and operational durability. The synergistic impact of alum-induced charge neutralisation and cactus mucilage polymer bridging enhanced floc production and treatment stability, hence reducing reliance on chemical coagulants. This hybrid technology offers specific advantages from a cleaner production perspective, including diminished chemical consumption, the integration of renewable local biomass, and improved process sustainability.

The findings support the integration of natural coagulants into hybrid water treatment systems as a viable method for resource-efficient, low-impact, and contextually appropriate drinking water solutions. Future research should encompass repeatable factorial experiments with statistical analysis, treated-water microbiology, residual aluminium, DOC, floc and sludge characterisation, sensitivity driven cost analysis, lifecycle evaluation, and pilot-scale validation.

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## AUTHOR CONTRIBUTIONS

HEM, PN, and JM: Conceptualisation, methodology, investigation, data curation, formal analysis, visualisation, and original draft preparation. DB, JN, and PT: Supervision, methodology review, validation, and critical revision of the manuscript. ZK and VK: Investigation, laboratory analysis, data validation, visualisation, data presentation, and manuscript editing.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information. The replicate-level experimental data supporting the findings of this study are provided with the article as Supplementary File S1: Experimental data. Additional information may be obtained from the corresponding author upon reasonable request.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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