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Effect of pH and Natural–Synthetic Coagulant Blends on Turbidity and Color Removal from Moche River Water

Aldo E. Pazos Zavaleta[a], Hugo A. Delgado Anderson[a], Adolfo E. Guerrero Escobedo[a,*], Ronald F. Rodriguez Espinoza[b], Yrwin F. Azabache Liza[c] , Joaquin J. Abarca Rodríguez[d]

[a]Universidad Nacional de Trujillo
[b]Universidad Autónoma del Perú
[c]Universidad Nacional de San Martín
[d]Universidad Nacional José Faustino Sánchez Carrión
aguerreroe@unitru.edu.pe

The Moche River is currently severely impacted by pollution originating from mining and agricultural activities, which compromises the quality of the water used for various purposes, including irrigation. This study evaluated the effectiveness of natural coagulants derived from *Moringa oleifera* (moringa) and *Caesalpinia spinosa* (tara), in combination with polyaluminum chloride (PAC), for improving the removal of turbidity and color from Moche River water. A simplex lattice experimental design comprising 33 trials was employed to assess the effects of different coagulant combinations at pH levels of 5, 7, and 9. The optimal results were achieved with a mixture of 80 ppm moringa and 40 ppm tara, resulting in 95.38% turbidity removal at pH 5 and 91.87% color removal at pH 9. However, the maximum removal achieved using all three coagulants was 77.48% for turbidity with 20 ppm moringa, 20 ppm tara, and 80 ppm PAC at pH 5. For color, the highest removal was 71.01% with 40 ppm moringa, 40 ppm tara, and 40 ppm PAC, also at pH 5.

1. Introduction

Human activities, particularly informal mining and intensive agriculture, have severely degraded river water quality across Latin America. Research conducted in the Peruvian Amazon reveals that artisanal gold mining significantly increases river turbidity and sediment concentrations, disrupting natural sedimentation cycles (Dethier et al., 2019). In various Latin American basins, these activities are identified as primary sources of water contamination, introducing heavy metals (Cd, Pb, U) and fertilizers that exceed permissible limits (Santana et al., 2020). These findings establish a direct link between mining, agrochemicals, and critical pollution levels in Peruvian and regional rivers.

Turbidity and color are essential indicators of water quality, as noted by Mebarki et al. (2024). High turbidity diminishes the efficacy of disinfection methods, such as chlorination, because suspended particles shield pathogens. Meanwhile, color—caused by organic matter (e.g., tannins, humates) or metals (e.g., Fe, Mn)—not only impacts the aesthetic quality of water but also signals contaminants that can generate toxic byproducts during disinfection. Therefore, the efficient removal of these parameters is crucial in treatment plants to ensure safe water.Plant-based coagulants are emerging as sustainable alternatives to conventional ones. Koul et al. (2022) highlight that *Moringa oleifera* extracts are renewable, non-toxic, biodegradable, and generate less sludge. Oliveira et al. (2024) demonstrated that 5 mL/L of moringa extract completely eliminates turbidity in water with 100 NTU. In Peru, *Caesalpinia spinosa* (tara), which is rich in tannins with colloidal agglomeration capacity, is also under investigation. These advances support the potential of these coagulants as cost-effective and eco-friendly alternatives to synthetic coagulants such as aluminum sulfate or polyaluminum chloride (PAC). Recent studies have explored synergies between natural and chemical coagulants to optimize removal. Balbinoti et al. (2024) tested blends of *Moringa oleifera* (MO) and PAC in low-turbidity waters, achieving 79% turbidity removal (compared to 66% with MO alone) and 90% color removal (compared to 65%) using a 70:30

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MO:PAC ratio. Such combinations reduce synthetic coagulant dosages without compromising efficiency, a key advantage for rural communities.Coagulation efficacy is critically dependent on pH and dosage. Shahzadi et al. (2024) employed an experimental design with sorghum as a coagulant, achieving 87.7% turbidity removal at pH 2 (40 mg/L) compared to 54% at pH 7 (55.7 mg/L), demonstrating that pH may be more decisive than dosage. In rural settings, where pH adjustment is challenging, achieving 50–60% removal under neutral conditions minimizes chemical use. These studies highlight the need to optimize variables in order to validate coagulants (whether natural or blended) in resource-limited communities.

2. Materials and Methods

2.1 Sample Collection

A 60 L water sample was collected on 29 August 2024 (dry season) from the lower basin of the Moche River, located in the Moche District (La Libertad Department, Peru; coordinates: 8°8'35.552"S, 79°0'47.351"W), in accordance with the National Protocol for the Monitoring of Surface Water Quality (ANA, 2016). Temperature, pH, turbidity, and electrical conductivity were measured according to APHA (2023), following the procedures outlined in Methods 2550 B – Field Method, 4500-H^+ B, 2130 B – Nephelometric Method, and 2510 B – Laboratory Method, respectively.

2.2 Coagulant Preparation

Two plant-based coagulant-flocculant agents were investigated: *Moringa oleifera* and *Caesalpinia spinosa* (tara). *Moringa oleifera* seeds, sourced from Sechura Province (Peru), were dehulled, crushed, and dried at 65 °C for 8 hours. The material was then ground into a fine powder and sieved through an #80 mesh (180 µm particle size). For *Caesalpinia spinosa*, commercially available tara gum powder was used. The third coagulant, polyaluminum chloride (PAC), was supplied by the Physicochemistry Laboratory of the National University of Trujillo. Stock solutions (5000 ppm) were prepared by dissolving 2.5 g of each material in a total volume of 0.5 L.

2.3 ATR Spectroscopy and Thermogravimetric Analysis of Natural Coagulants

The fine powders of *Moringa oleifera* and *Caesalpinia spinosa* were characterized using attenuated total reflectance (ATR) spectroscopy (PerkinElmer Spectrum Two) to identify functional groups responsible for coagulation. Thermogravimetric analysis (TGA) was performed using a TA Instruments TGA 5500 to evaluate thermal stability and composition.

2.4 SEM Microphotography and EDS Analysis

Morphological characterization of the natural coagulants was conducted via Scanning Electron Microscopy (SEM; Thermo Fisher Scientific) at a 50 µm scale to visualize porous structures. Energy Dispersive X-ray Spectroscopy (EDS) analysis was employed to quantify surface elements (e.g., carbon, oxygen, ash residues).

2.5 Water Sample pH Adjustment

The 60 L sample was divided into three 20 L aliquots. pH was adjusted to 5 (7.1 mL of 0.1 M HCl), 7 (0.1 mL of 0.1 M HCl), and 9 (6.4 mL of 0.1 M NaOH) using a Jenway 3510 pH meter.

2.6 Coagulant Application

A two-phase agitation protocol was implemented: rapid mixing (120 rpm, 2 min) followed by slow mixing (50 rpm, 5 min) and sedimentation (20 min). A simplex lattice design with 33 trials (3 replicates each) was used. The concentrations of each coagulant were 0, 20, 40, 80, and 120 ppm, with a total concentration of 120 ppm in each mixture.

2.7 Color Removal

Pre-treatment: Color was measured according to UNE-EN ISO 7887:2012 (Method B) using a Spectronic 20 UV-Vis spectrophotometer (580 nm) to determine the spectral absorption coefficient.
Post-treatment: Measurements were repeated post-coagulation, and color quantification followed the same standard.

$$Spectral\ absorption\ coefficient = \frac{A}{d} x f \tag{1}$$

Where:
A: absorbance of the sample (at 580 nm), *d*: cell thickness (mm), f: conversion factor from mm to m = 1000.
To find the percentage of color removal, the following equation was used:

$$Percentage\ of\ color\ removal = \frac{C_0 - C_f}{C_0} x100 \tag{2}$$

Where:
C_0: initial spectral absorption coefficient (m^{-1}), C_f: final spectral absorption coefficient (m^{-1}).

2.8 Turbidity Removal

Turbidity was measured in Nephelometric Turbidity Units (NTU). The initial turbidity (T_0) of 20 L water samples was recorded at pH levels of 5, 7, and 9 prior to the addition of coagulants. After the application of the coagulants and a 20-minute settling period, the final turbidity (T_f) was measured. Turbidity values were determined using a Hach 2100 Q turbidimeter. The percentage of turbidity removal was calculated using the following equation:

$$Turbidity\ removal\ percentage = \frac{T_0 - T_f}{T_0} x100 \tag{3}$$

Where:
T_0: initial turbidity (NTU), T_f: final turbidity (NTU).

3. Results and Discussions

3.1 Characterization of the water in the Moche River

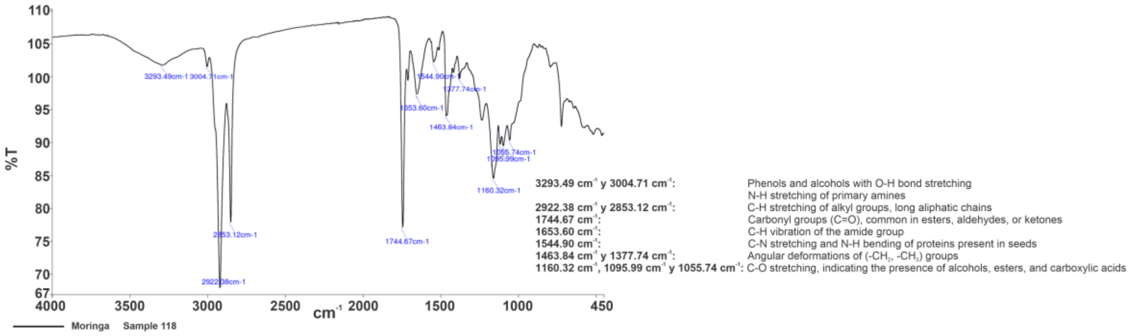
Table 1 presents the results of the physicochemical analyses of water from the Moche River. It is important to note that these parameters fluctuate in response to seasonal variations and the discharge of effluents, particularly those originating from illegal mining activities. These discharges contribute to a decrease in pH, as well as an increase in turbidity and electrical conductivity.

Table 1: Physicochemical parameters of the water of the Moche River

PARAMETERS	UNITS	RESULTS
Temperature	°C	17
pH	N/A	7.6
Turbidity	NTU	58.01
Electrical conductivity	µS/cm	1021

3.2 ATR Characterization of Natural Coagulants

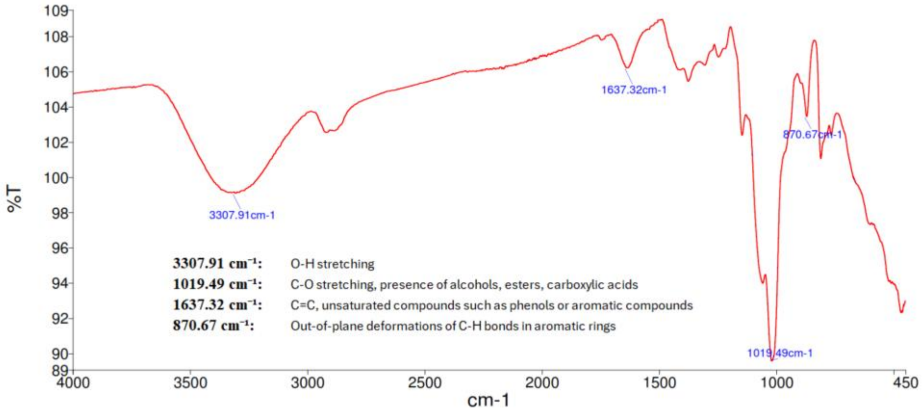
The ATR spectrum of *Moringa oleifera* confirms the presence of key functional groups that contribute to its coagulating capacity. Carbonyl (C=O) and alkyl groups facilitate coagulation by destabilizing colloidal particles, while C–O groups enhance the adsorption of impurities. According to Zaid et al. (2019), the coagulating properties are primarily attributed to the presence of cationic proteins, which interact with these functional groups. These mechanisms collectively contribute to the reduction of both turbidity and color in treated water.



3293.49 cm^{-1} y 3004.71 cm^{-1}:	Phenols and alcohols with O-H bond stretching N-H stretching of primary amines
2922.38 cm^{-1} y 2853.12 cm^{-1}:	C-H stretching of alkyl groups, long aliphatic chains
1744.67 cm^{-1}:	Carbonyl groups (C=O), common in esters, aldehydes, or ketones
1653.60 cm^{-1}:	C-H vibration of the amide group
1544.90 cm^{-1}:	C-N stretching and N-H bending of proteins present in seeds
1463.84 cm^{-1} y 1377.74 cm^{-1}:	Angular deformations of ($-CH_2$, $-CH_3$) groups
1160.32 cm^{-1}, 1095.99 cm^{-1} y 1055.74 cm^{-1}:	C-O stretching, indicating the presence of alcohols, esters, and carboxylic acids

Figure 1: Moringa Oleifera ATR Spectrum

The ATR spectrum of *Caesalpinia spinosa* (tara) confirms the presence of hydroxyl and ester groups, which are responsible for its coagulating ability by promoting water retention and the formation of floc networks that entrap suspended particles. Valeriano-Mamani and Matos-Chamorro (2019) reported that these functional groups present in tara contribute to higher efficiency in turbidity removal from aqueous solutions.



3307.91 cm^{-1}: O-H stretching
1019.49 cm^{-1}: C-O stretching, presence of alcohols, esters, carboxylic acids
1637.32 cm^{-1}: C=C, unsaturated compounds such as phenols or aromatic compounds
870.67 cm^{-1}: Out-of-plane deformations of C-H bonds in aromatic rings

Figure 2: ATR spectrum of Caesalpinia spinosa (tara)

3.3 Thermogravimetric Characterization of Natural Coagulants

Figure 3 shows the TGA curve of *Moringa oleifera*. The initial mass loss (30–150 °C) is associated with the evaporation of surface water, a behavior observed in biological materials. Between 150 °C and 400 °C, a mass reduction occurs, corresponding to the thermal degradation of proteins and polysaccharides, which are responsible for moringa's coagulating ability due to the presence of functional groups such as –OH, –COOH, and $–NH_2$. Above 400 °C, the degradation slows down due to the combustion of more refractory carbonaceous residues (Teixeira et al., 2022). The first mass loss (30–150 °C) in *Caesalpinia spinosa* is also attributed to the evaporation of water retained by hydroxyl groups (–OH) (Valeriano-Mamani and Matos-Chamorro, 2019). Between 150 °C and 400 °C, the mass reduction is mainly due to the degradation of proteins and polysaccharides, with ester (–COOR) and ether (–O–) groups facilitating the formation of flocs. Above 400 °C, recalcitrant carbonaceous residues are present, characteristic of tara's biopolymers.

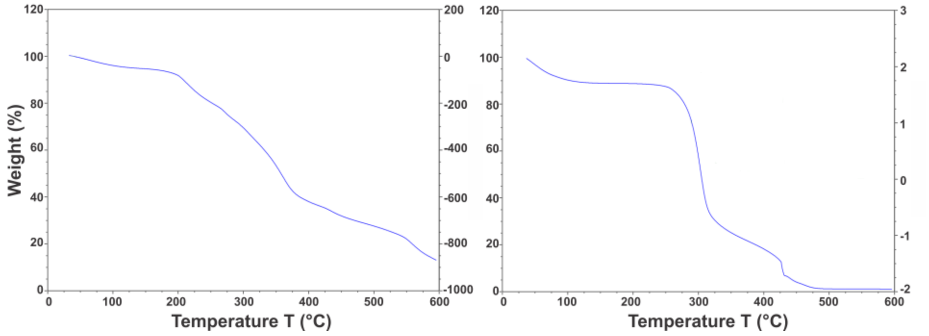


Figure 3: (a) Moringa oleifera (b) Caesalpinia spinosa

3.4 SEM and EDS Characterization of Natural Coagulants

The SEM images of *Moringa oleifera* reveal a highly rough and porous structure, as shown in Figure 4(a). This morphology promotes the adsorption of suspended particles and enhances the removal efficiency of turbidity and color from water (Baquerizo-Crespo et al., 2020). The EDS analysis, illustrated in Figure 4(b), indicates carbon (62.1%) and oxygen (36.1%), typical of organic materials rich in biopolymers such as proteins and polysaccharides. The EDS spectrum confirms dominant peaks of C and O, along with traces of magnesium and phosphorus.

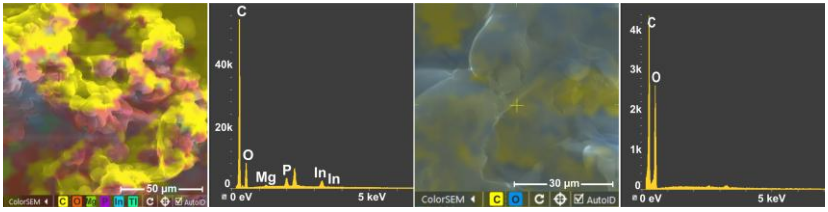


Figure 4: (a) mag 1000 x, 30kV SEM image of Moringa oleifera; (b) Elemental analysis of Moringa oleifera; (c) mag 1000 x, 30kV SEM image of Caesalpinia spinosa; (d) Elemental analysis of Caesalpinia spinosa.

These elements do not interfere with the coagulating capacity, which is attributed to the cationic proteins present in moringa. *Caesalpinia spinosa* (tara) displays a more compact and homogeneous surface, as seen in Figure 4(c), suggesting a different flocculation mechanism for trapping colloidal particles (Teixeira et al., 2022). The EDS analysis reveals a composition of 53.3% oxygen and 46.7% carbon, indicating a higher presence of hydroxyl and carboxyl groups. No significant impurities are observed in Figure 4(d), which supports its ability to form large and stable flocs.

3.5 Removal of turbidity and color

Figures 5 and 6 present the response surface plots for turbidity and color removal, respectively. The letters A, B, and C correspond to *Moringa oleifera*, *Caesalpinia spinosa*, and polyaluminum chloride (PAC), respectively. At a concentration of 120 ppm, A achieved a turbidity removal efficiency of 91.54% at pH 9; B reached 87.55% at the same pH; while C exhibited a removal efficiency of 78.44% at pH 5.

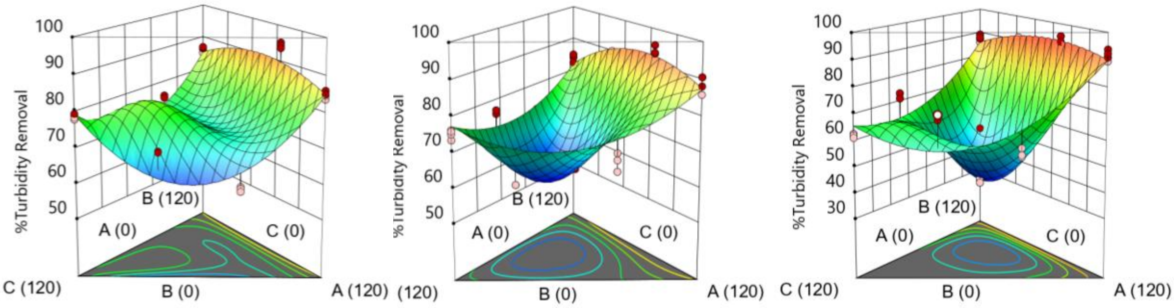


Figure 5: 3D surface for turbidity removal at the following pH values: (a) 5, (b) 7 and (c) 9.

At a concentration of 120 ppm, A achieved a color removal efficiency of 87.21% at pH 9; B reached 81.57% at pH 5; while C exhibited a removal efficiency of 72.17% at pH 9.

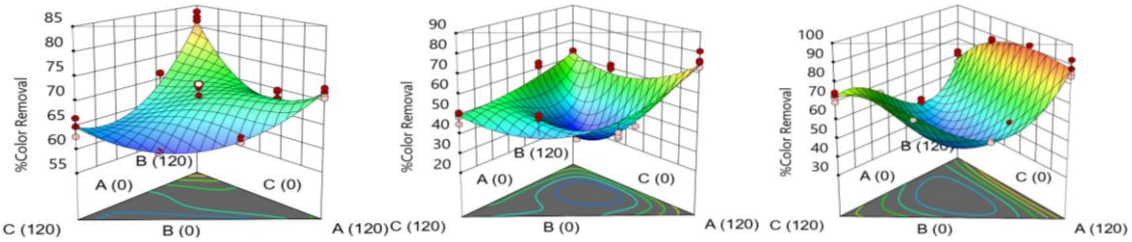


Figure 6: 3D surface for color removal at the following pH values: (a) 5, (b) 7 and (c) 9.

The highest turbidity removal efficiencies were achieved with 80 ppm of A and 40 ppm of B, reaching 94.51% at pH 5, 93.85% at pH 7, and 93.53% at pH 9. For color removal, the best results were obtained with 120 ppm of B at pH 5 (81.57%), 120 ppm of A at pH 7 (76.05%), and 80 ppm A and 40 ppm B at pH 9 (89.39%). The maximum turbidity removal with all three coagulants was 77.48%, achieved with 20 ppm of A, 20 ppm of B, and 80 ppm of C. Meanwhile, the highest color removal was 69.11%, obtained with an even distribution of 40 ppm of each coagulant. Acidic pH protonates cationic proteins, favoring interaction with anionic colloids and turbidity removals greater than 95%, similar to that reported by Desta et al. (2021). At alkaline pH, the phenolic groups of tannins are deprotonated, allowing adsorption and molecular bridging of colored molecules. Tomasi et al. (2025) reported color removals greater than 90% in these pH ranges, confirming this trend. No previous studies have shown the mixture of three coagulants. The combination of moringa and tara may allow a reduction in chemical coagulants and be suitable for rural areas near the river (Badawi et al., 2023). Plant-based bio-coagulants are biodegradable, less toxic, and generate minimal sludge (Kurniawan et al., 2020). A life cycle analysis from production to extraction is necessary. It should be noted that this study does not include field trials and does not consider seasonal variability in the river. Additional doses should be applied according to the river water quality parameters. No ecotoxicity studies of the residues were conducted.

4. Conclusions

Attenuated Total Reflectance–Fourier Transform Infrared (ATR-FTIR) spectroscopy analyses identified functional groups, including carbonyls, hydroxyls, esters, and C–O bonds, in *Moringa oleifera* and *Caesalpinia* *spinosa*, all of which are essential for their coagulating activity. In *Moringa oleifera*, carbonyl and alkyl groups contribute to colloidal destabilization, whereas in *Caesalpinia spinosa*, hydroxyl and carboxyl groups promote the formation of larger and more stable flocs. Thermogravimetric analysis (TGA) demonstrated that both natural coagulants exhibit good thermal stability, with mass losses primarily associated with water evaporation and organic compound decomposition occurring between 150 °C and 400 °C. Scanning Electron Microscopy (SEM) micrographs revealed a porous structure in *Moringa oleifera*, enhancing particle adsorption, while *Caesalpinia spinosa* exhibited a more compact surface, which favors floc stability. The highest turbidity removal efficiency, 94.51%, was achieved with a combination of 80 ppm of *Moringa oleifera* and 40 ppm of *Caesalpinia spinosa* at pH 5. Meanwhile, the maximum color removal, 89.39%, was observed at pH 9 using the same coagulant concentrations.

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