

Article

Moringa oleifera Lam as a Biocoagulant in the Treatment of Water from the Amazon River in the Amazon Region, Brazil

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Abstract

Biocoagulants derived from *Moringa oleifera* Lam seeds are a sustainable alternative for water clarification, but require preparation adapted to the treatment of the dark waters of the Amazon River. This study compared the effectiveness of three coagulant preparation methods from moringa seeds: powder (B1), saline solution (B2), and aqueous solution (B3) in the clarification of samples collected on the shore of Macapá (Amapá—AP), Brazil. The tests were performed using a jar test (fast mixing of 100 rpm for 3 min and slow mixing of 20 rpm for 15 min), with dosages of 20 to 200 mg·L^{−1}, and sedimentation times between 10 and 60 min. The optimized conditions were: 80 mg·L^{−1}/20 min (B1), 40 mg·L^{−1}/30 min (B2), and 40 mg·L^{−1}/40 min (B3). The maximum removals achieved by clarification were as follows: apparent color (92.6%), turbidity (79.4%), chloride (70.9%), ammonia (81.2%), aluminum (99.1%), copper (85.4%), iron (85.8%), and manganese (100.0%). The saline solution was the most efficient. Filtration brought additional improvements to the treated water. It was found that the moringa coagulant was effective in removing contaminants from the waters of the Amazon River, standing out as a green, sustainable, and low-cost technology. However, disinfection would be necessary to improve its microbiological quality.

Keywords: apparent color; biocoagulant; coagulation; flocculation; jar test; turbidity



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1. Introduction

Access to safe drinking water of adequate quality and quantity is essential for public health, well-being, and sustainable development all over the world [1]. The Amazon Basin, the largest in the world concerning freshwater volume [2], holds vast water resources. However, this abundance does not automatically ensure the safe supply of treated water to the population. In Brazil's Northern region, for example, significant inequalities persist in the city of Macapá (AP), where 45.6% of the population still lacks access to potable water [3].

Conventional water treatment systems typically involve the coagulation, flocculation, sedimentation, filtration, and disinfection stages to meet current drinking water standards [4]. Among these stages, coagulation and flocculation are considered fundamental to the success of the water clarification. Coagulation promotes the neutralization of the

charges of colloidal particles of the water [5], while flocculation facilitates the aggregation of these particles into larger and denser flocs [6,7], which are easier to remove in the subsequent stages. Thus, the coagulation-flocculation unit contributes significantly to the overall efficiency of the treatment system, optimizing the removal of apparent color, turbidity, organic matter, and microorganisms [5–8]. After this stage, sedimentation enables the settling of the flocs, filtration complements the retention of remaining particles, and disinfection ensures the elimination of pathogenic microorganisms [8].

For coagulation, chemical coagulants based on aluminum and iron salts are often used, but they can compromise water quality, produce toxic waste, and cause equipment corrosion [6,9,10]. Moreover, the accumulation of these metals, particularly aluminum, is risky to human health [11,12].

Regarding such impacts, there is an increasing interest in natural coagulants (biocoagulants or biopolymers) produced from available biomass, which are biodegradable, low in toxicity, and efficient. Their use generates less waste regarding chemical products, and the by-products are promising as fertilizers. In addition, these coagulants also reduce costs and the production of toxic sludge [10,13,14].

As moringa (*Moringa oleifera* Lam) seeds contain approximately 40% protein, they are among the most promising natural coagulants [14,15]. These proteins possess a highly charged structure and high molecular weight, which provides their coagulating activity [16]. Their physicochemical performance consists of charge neutralization through protein adsorption [10,17–19]. In addition, moringa exhibits antimicrobial properties, being capable of inactivating pathogenic bacteria such as *Escherichia coli* [13,20].

Numerous studies have demonstrated the effectiveness of moringa in water treatment, both as powdered seed and solutions [21–26]. However, factors such as raw water quality, coagulant concentration, and preparation method directly influence the results, making it essential to identify the ideal combination of these elements to optimize treatments [19]. This challenge becomes even more significant in the Amazon region, where the water from the Amazon River presents high turbidity, a large amount of organic matter, and considerable seasonal variation [27]. These conditions require specific care to ensure the proper performance of natural coagulants, highlighting the importance of using solutions adapted to the local context.

Therefore, this study aimed to compare the effectiveness of three different preparation methods of coagulants from the moringa seeds in clarifying waters from the waterfront of the Amazon River. The study focused on optimizing dosages and sedimentation times, followed by the application of a filtration step for further improvements of the water quality.

2. Materials and Methods

2.1. Water Sampling

The raw surface water was collected from the waterfront of the Amazon River in Macapá (AP), at the geographic coordinates 0°00′55.6″ N and 51°03′22.8″ W (Figure 1). Approximately 100 L of water was collected directly from the river surface and stored in 25 L containers, in a freezer (Gelopar, GHBS 411L, Curitiba, PR, Brazil) for preservation until the tests were performed.

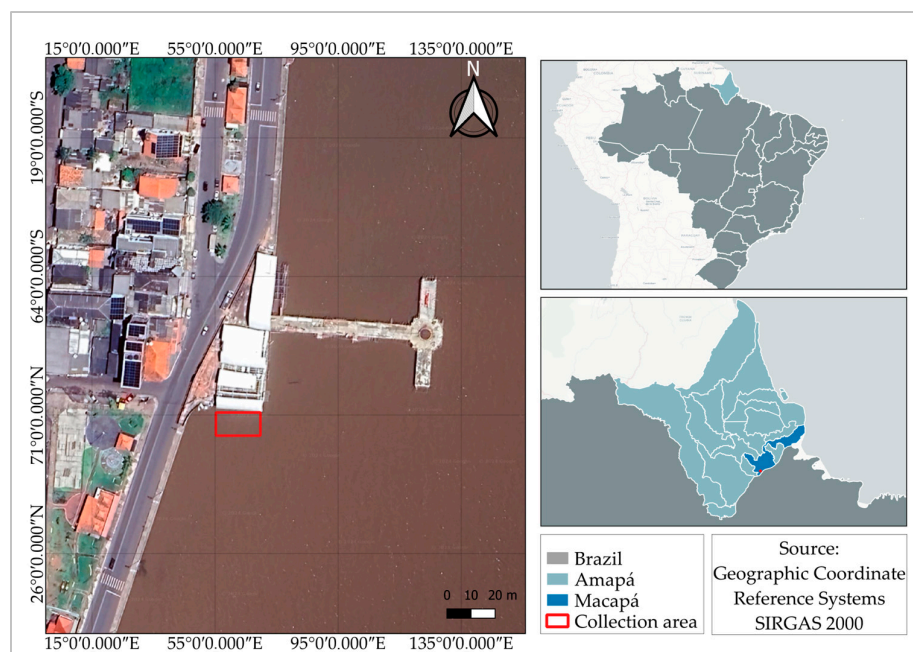


Figure 1. Location of the collection site.

2.2. Preparation of the Biocoagulants

Moringa seeds were shelled to obtain the powder, and 15 g were weighed (Ohaus, PA214CP, Newark, NJ, EUA), dried in an oven (Vulcam, EESCRA-1150-BI, Araucária, PR, Brazil) at 40 °C until reaching constant weight (12–24 h), and ground in a blender (Mondial, L-550-B, Manaus, AM, Brazil) for 2 min [26]. The powder was used as a direct coagulant and for the preparation of saline and aqueous solutions.

The solutions were prepared at a concentration of 1% (*w/v*). For the saline solution, a 1 M NaCl solution (Alphatec, São Bernardo do Campo, SP, Brazil) was used, and distilled water was used for the aqueous solution. Each solution was homogenized in a blender (Mondial, L-550-B, Manaus, AM, Brazil) for 2 min and then stirred for 30 min on a magnetic stirrer (Ion, HJ-5, Changzhou, China). After this step, the solution was filtered through qualitative filter paper (Nalgon, Itupeva, SP, Brazil), with a grammage of 80 g.m^{−2} and a diameter of 9 cm [28].

2.3. Coagulation, Flocculation, and Sedimentation Tests

The clarification tests were conducted using a six-unit jar test apparatus (Milan, 603M6, Colombo, PR, Brazil). Each beaker received 2 L of raw water at room temperature (25 ± 2 °C). Operational conditions were standardized with rapid mixing at 100 rpm for 3 min for coagulation, followed by slow mixing at 20 rpm for 15 min for flocculation. These values were selected based on previous studies that indicate they are effective in promoting floc formation and stability in waters with similar physical characteristics to those analyzed [26].

The applied dosages were 20, 40, 60, 80, 100, 120, 140, 160, 180, and 200 mg.L^{−1}. Sedimentation time was evaluated at intervals of 10, 20, 30, 40, 50, and 60 min, in triplicate. In addition to the treatments, a control trial was included, without the addition of coagulant.

2.4. Definition of Optimized Conditions

In the optimization stage, ideal dosages and sedimentation times for each preparation method were evaluated based on apparent color and turbidity removal parameters.

All analyses were performed in triplicate, and the data were processed using Minitab Statistical Software, version 22 (Minitab, LLC, State College, PA, USA) with contour plots.

This program calculates intermediate values between existing measurement points for dosages and sedimentation times through data interpolation, allowing for the identification of optimal conditions.

2.5. Filtration

After optimization, the tests were repeated using the previously defined optimal dosages and sedimentation times, followed by the filtration stage using a rapid downward-flow dual-media filter with depth filtration action, made of a plastic tube measuring 28 cm in height and 6 cm in diameter. The filter media, with a total height of 13 cm, consisted of 40% sand (0.6–1.2 mm) and 60% anthracite coal (0.9–1.0 mm), supported by a 4 cm layer of gravel. The adopted hydraulic loading rate was at least $240 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ [26,29], resulting in a total hydraulic head of 7.7 cm. The total filtration time was 7 min, with samples collected after 5 min of operation (Figure 2).



Figure 2. Design of the rapid downward-flow dual-media filter.

2.6. Physicochemical and Microbiological Analyses

The following physicochemical and microbiological parameters were evaluated for the raw surface water, clarified water under optimized conditions, and filtered water: apparent color (uH), turbidity (NTU), chloride (Cl^-), ammonia (NH_3), pH, aluminum (Al), copper (Cu), iron (Fe), manganese (Mn), total coliforms, and *E. coli*, according to the methodologies described in the Standard Methods for the Examination of Water and Wastewater [30]. The equipment used included: a spectrophotometer (Hach, DR3900, Düsseldorf, NW, Germany), a turbidimeter (Akso, Turbimax, São Leopoldo, RS, Brazil), a pH meter (Hach, HQ4300, Loveland, CO, USA), a bacteriological incubator (Odontobras, ECB 1.1, Ribeirão Preto, SP, Brazil), a Sealer (Idexx Quanti-Tray Sealer, model 2X, Westbrook, ME, USA), and an ultraviolet (UV, Piracicaba, SP, Brazil) chamber. The overall methodology of the work is summarized in Figure 3.

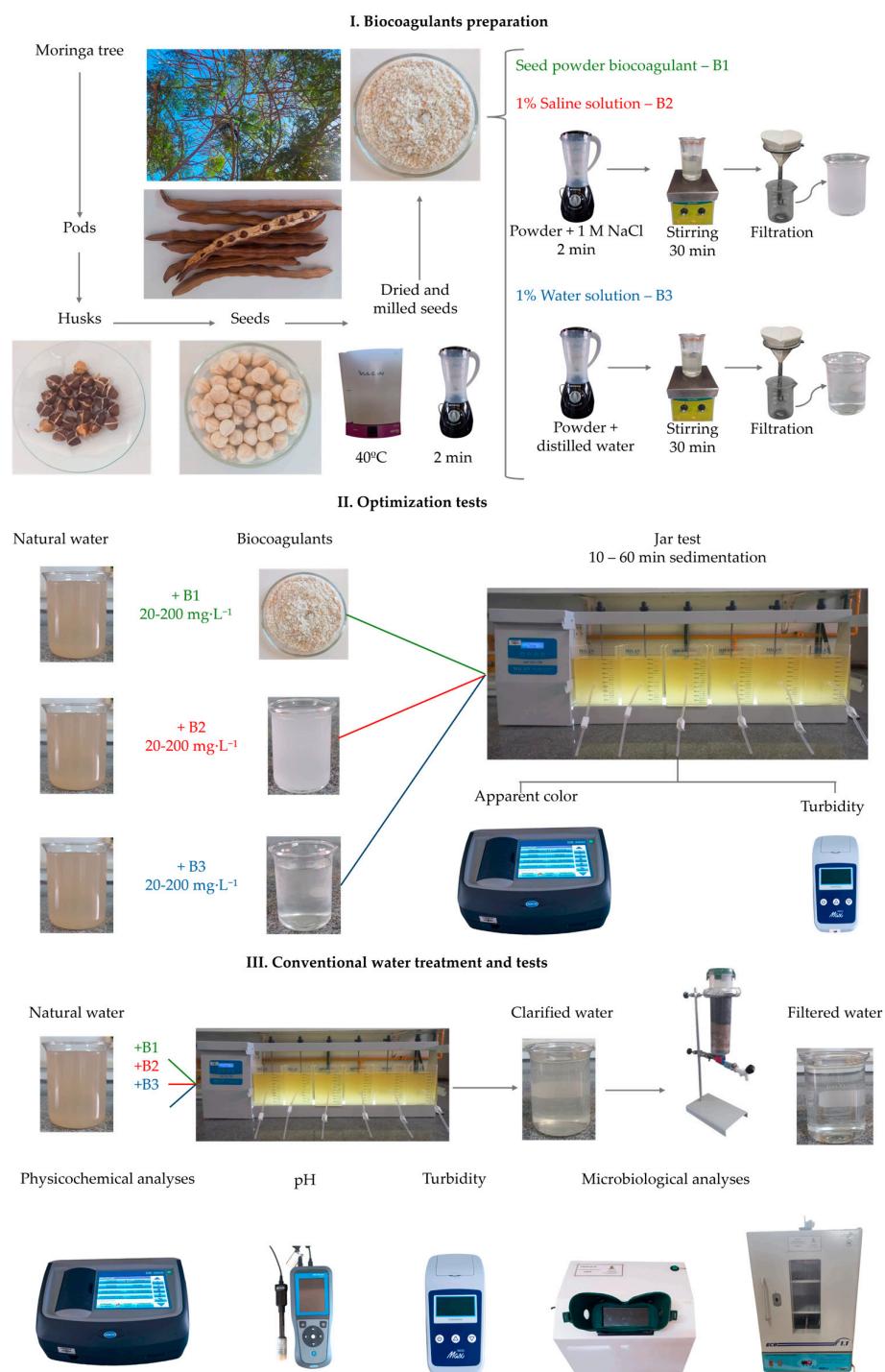


Figure 3. Scheme of the overall methodology.

3. Results and Discussion

3.1. Optimization of Dosage and Sedimentation Parameters

For moringa powder, the dosage of 20 mg·L⁻¹ resulted in low efficiency and was similar to that of the control sample (0 mg·L⁻¹ of coagulant). In contrast, concentrations between 40 mg·L⁻¹ and 100 mg·L⁻¹ significantly removed apparent color and turbidity. From 120 mg·L⁻¹ to 200 mg·L⁻¹, the removal efficiency tended to stabilize. Furthermore, the sedimentation time directly influenced the results (Figures 4 and 5).

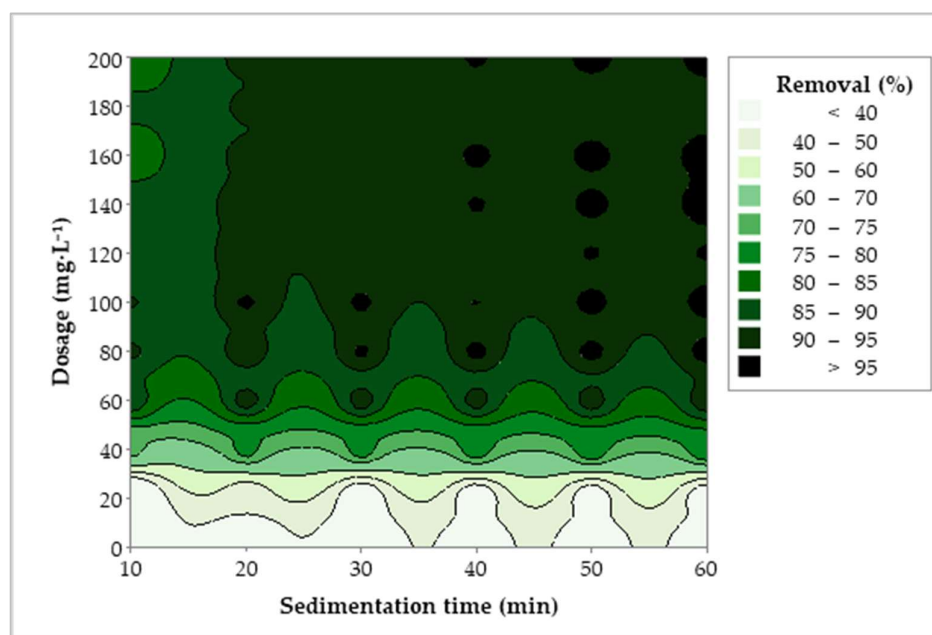


Figure 4. Removal of apparent color as a function of dosage and sedimentation using moringa powder as a biocoagulant.

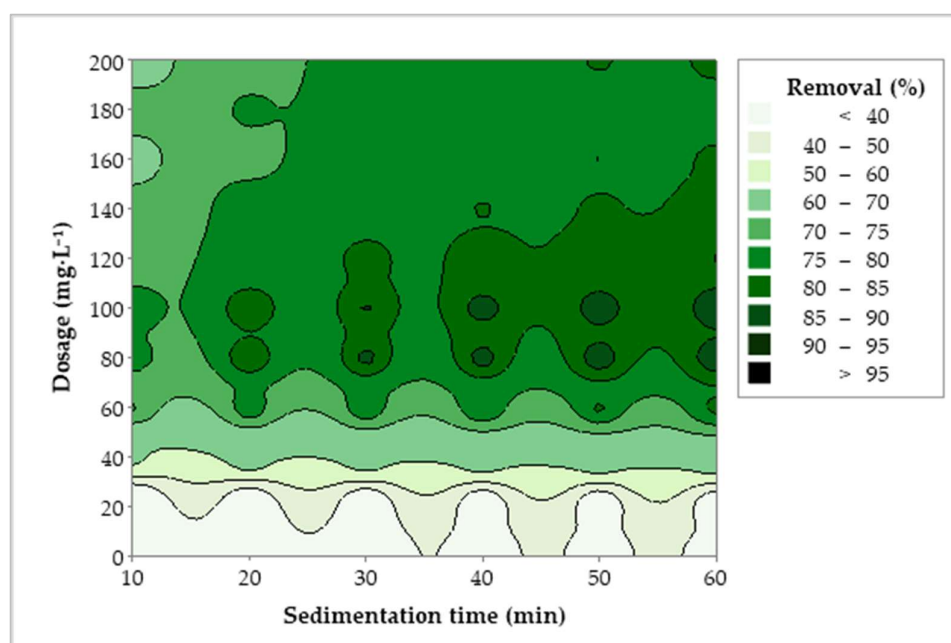


Figure 5. Removal of turbidity as a function of dosage and sedimentation using moringa powder as a biocoagulant.

The raw water showed an apparent color of (797.6 ± 1.53) uH and turbidity of (94.3 ± 2.08) NTU. The tests were conducted with sedimentation times ranging from 10 to 60 min. The removal of the control ($0 \text{ mg}\cdot\text{L}^{-1}$) treatment ranged from $(1.5 \pm 1.96)\%$ to $(18.6 \pm 0.47)\%$ for apparent color and from $(13.3 \pm 1.40)\%$ to $(28.9 \pm 0.78)\%$ for turbidity, which are below the values obtained by using moringa biocoagulant. Up to 39.0% of turbidity removal without a coagulant was achieved in the literature [17]. According to Ordinance GM/MS n°. 888/2021, the maximum allowed values for drinking water are 15 uH for apparent color and 5 NTU for turbidity [31]. Therefore, the use of a coagulant, such as moringa seeds, is essential to enhance clarification and meet drinking water standards [32].

The dosage of $20 \text{ mg}\cdot\text{L}^{-1}$ resulted in apparent color removals between $(11.8 \pm 2.47)\%$ and $(29.7 \pm 1.39)\%$, like the control sample; hence, it had inefficient particle agglomeration [33]. The suitable dosage of a coagulant is essential for forming flocs, leading to effective impurity removal [34].

Applying a $40 \text{ mg}\cdot\text{L}^{-1}$ dosage, the apparent color removal ranged from $(72.0 \pm 0.26)\%$ to $(79.4 \pm 0.71)\%$, while the turbidity removal varied from $(61.5 \pm 0.96)\%$ to $(67.5 \pm 0.27)\%$. When the dosage was increased to $60 \text{ mg}\cdot\text{L}^{-1}$, removal rates were $(88.8 \pm 0.63)\%$ to $(93.6 \pm 0.65)\%$ for apparent color and $(75.3 \pm 0.43)\%$ to $(81.1 \pm 0.18)\%$ for turbidity, a significant improvement. A similar performance was reported with removals of 79.8% for apparent color and 84.0% for turbidity in the Pirapó River water, Maringá (PR), Brazil, using a $50 \text{ mg}\cdot\text{L}^{-1}$ dosage of moringa within the same concentration range [28].

Raising the dosage to $80 \text{ mg}\cdot\text{L}^{-1}$ and $100 \text{ mg}\cdot\text{L}^{-1}$ allowed the achievement of removal rates of $(91.1 \pm 1.01)\%$ to $(97.4 \pm 0.40)\%$ for apparent color and $(77.0 \pm 1.44)\%$ to $(89.0 \pm 0.12)\%$ for turbidity since there were more proteins available to form stable flocs [35]. The efficiency of the highest dosages, between $120 \text{ mg}\cdot\text{L}^{-1}$ and $200 \text{ mg}\cdot\text{L}^{-1}$, tended to stabilize or slightly reduce, with values ranging from $(80.0 \pm 1.69)\%$ to $(97.4 \pm 0.22)\%$ for apparent color and from $(63.9 \pm 1.65)\%$ to $(85.1 \pm 0.50)\%$ for turbidity. This behavior is associated with protein excess in the solution, providing extra positive charges, and altering the zeta potential of the suspension, which hinders the formation of stable flocs [18].

Sedimentation time proved to be a determining factor in removal efficiency, with better results observed between 20 and 30 min, despite continued gains up to 60 min. In general, longer sedimentation times tend to improve efficiency by promoting the deposition of flocculated particles [36,37]. However, even with shorter durations, good clarification can be achieved if the coagulant preparation and water characteristics are suitable [23].

In light of this, the results demonstrated that apparent color and turbidity removal rates varied according to dosage and sedimentation time, corroborating the findings of [38,39].

The saline moringa solution showed high efficiency in removing apparent color and turbidity, even at dosages of $20 \text{ mg}\cdot\text{L}^{-1}$ to $40 \text{ mg}\cdot\text{L}^{-1}$. From $60 \text{ mg}\cdot\text{L}^{-1}$ up, the results remained stable up to $200 \text{ mg}\cdot\text{L}^{-1}$. Regarding sedimentation time, periods between 20 and 30 min were already sufficient to achieve efficiencies like those obtained with longer times (Figures 6 and 7).

At a dosage of $20 \text{ mg}\cdot\text{L}^{-1}$, an efficiency in the removal of apparent color of $(73.8 \pm 0.32)\%$ to $(78.8 \pm 0.94)\%$, and for turbidity of $(63.2 \pm 0.69)\%$ to $(68.9 \pm 0.37)\%$ was observed. The dosage of $40 \text{ mg}\cdot\text{L}^{-1}$ presented removal of apparent color between $(89.0 \pm 1.78)\%$ and $(94.7 \pm 0.52)\%$, and of turbidity between $(75.4 \pm 1.07)\%$ and $(86.6 \pm 0.06)\%$, evidencing adequate performance. From the dosage of $60 \text{ mg}\cdot\text{L}^{-1}$ to $200 \text{ mg}\cdot\text{L}^{-1}$, the removal of apparent color varied between $(61.5 \pm 1.43)\%$ and $(97.4 \pm 0.95)\%$, while turbidity varied between $(52.7 \pm 1.21)\%$ and $(93.1 \pm 0.94)\%$.

Overall, the effectiveness of the moringa saline solution for treating water was observed in previous studies that reported up to 90.0% of turbidity removal [17], 82.9% of apparent color, and 89.3% of turbidity removal [28].

It was observed that, although increasing the sedimentation time improved the results, dosages up to $40 \text{ mg}\cdot\text{L}^{-1}$ showed similar efficiencies to those between $60 \text{ mg}\cdot\text{L}^{-1}$ and $200 \text{ mg}\cdot\text{L}^{-1}$, regardless of short sedimentation times of 20 to 30 min. This performance is associated with the action of NaCl, which enhances coagulant activity [21]. Therefore, it is more advantageous to use low dosages in combination with shorter sedimentation times [38].

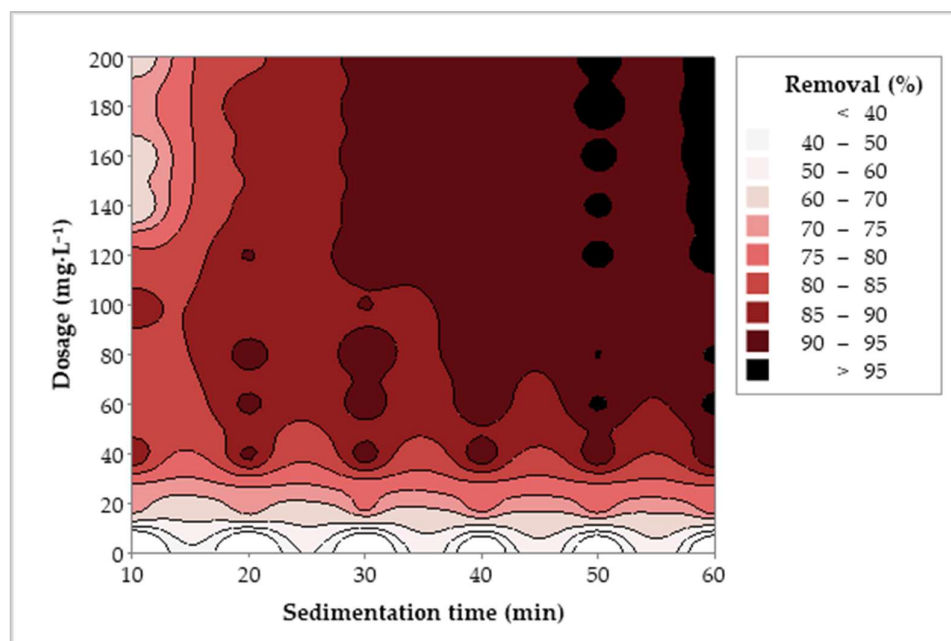


Figure 6. Removal of apparent color as a function of dosage and sedimentation using moringa saline solution as biocoagulant.

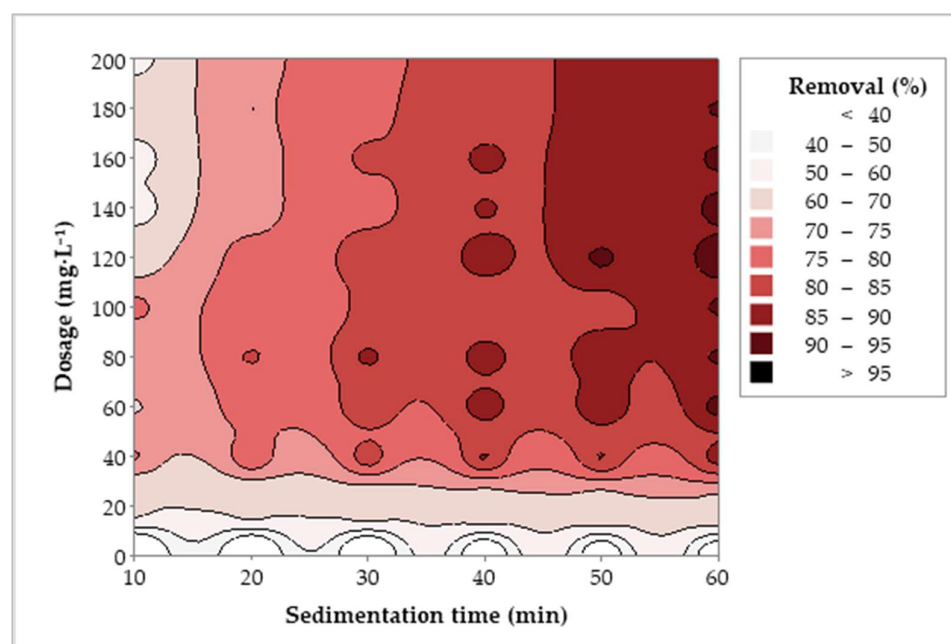


Figure 7. Removal of turbidity as a function of dosage and sedimentation using moringa saline solution as biocoagulant.

In this study, the saline solution showed superior performance compared to moringa powder, confirming previous findings that reported up to 7.4 times greater efficiency with saline extraction [40]. This performance is related to the increase in ionic strength promoted by the addition of salt, which enhances protein solubilization and the availability of active compounds responsible for coagulation [17,41].

Thus, while the coagulation mechanism of the powder tends toward adsorption and charge neutralization [10,42], the activation mechanism of moringa in saline solution is not yet fully understood and requires further investigation [28].

The aqueous moringa solution showed low percentages of apparent color and turbidity removal, even with increased dosages between $20 \text{ mg}\cdot\text{L}^{-1}$ and $200 \text{ mg}\cdot\text{L}^{-1}$. Furthermore, sedimentation time did not influence the results, indicating the low efficiency of this method in the water clarification process (Figures 8 and 9).

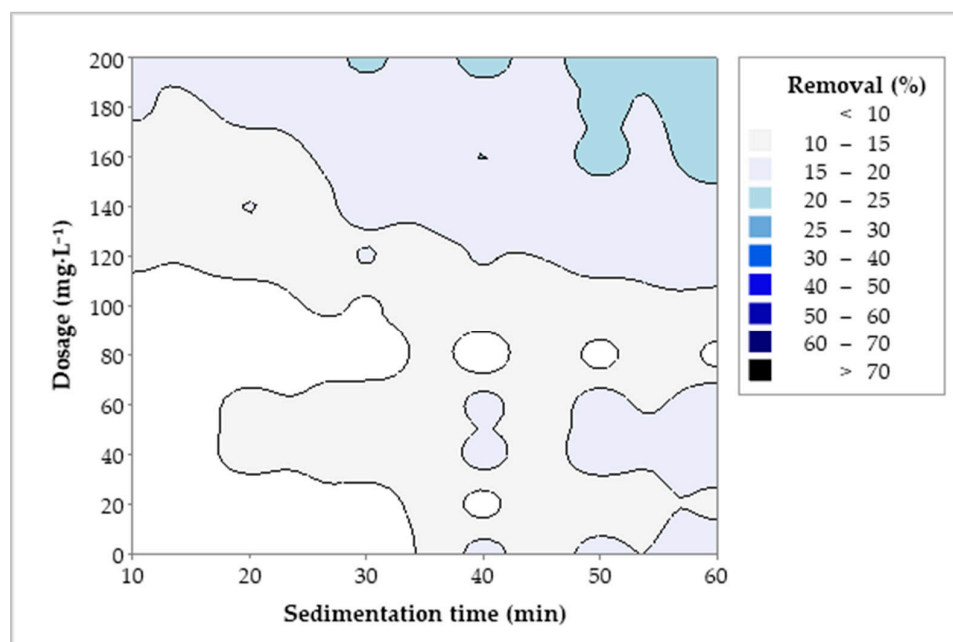


Figure 8. Removal of apparent color as a function of dosage and sedimentation using moringa aqueous solution as biocoagulant.

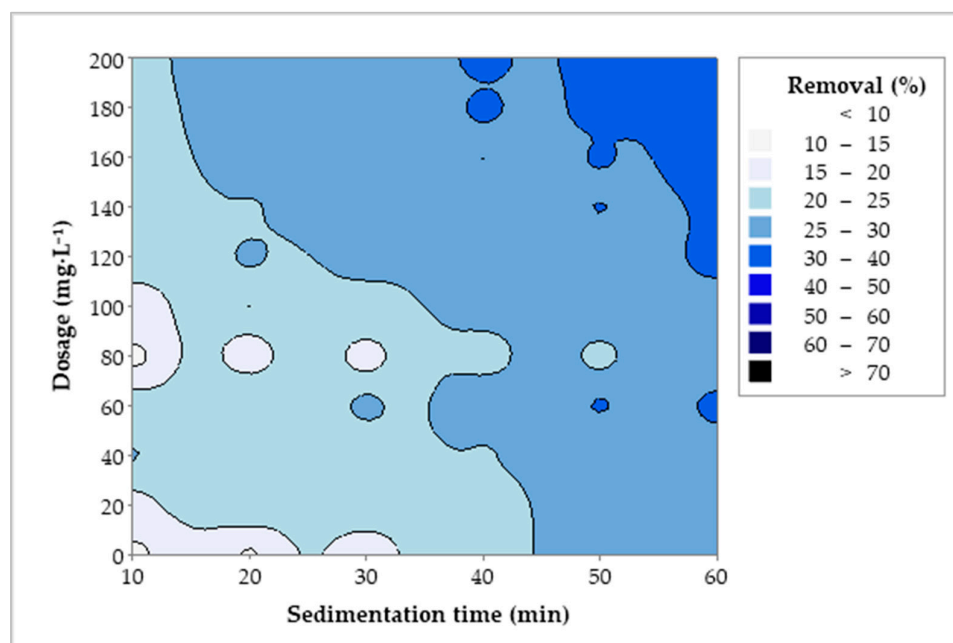


Figure 9. Removal of turbidity as a function of dosage and sedimentation using moringa aqueous solution as biocoagulant.

Dosages ranging from 20 to $200 \text{ mg}\cdot\text{L}^{-1}$ resulted in removals of $(3.9 \pm 1.93)\%$ to $(24.0 \pm 1.23)\%$ for apparent color and $(13.2 \pm 0.55)\%$ to $(33.3 \pm 0.22)\%$ for turbidity, showing similar performance to that of the control sample. Increasing the sedimentation time did not lead to significant improvements, due to the formation of small and loosely compacted flocs, which hinder water clarification [7].

Higher protein concentrations are directly related to increased coagulant activity, while extraction with water results in lower protein concentration, thereby reducing coagulant efficiency [43]. The solubility of coagulant proteins is limited in aqueous media, whereas saline solutions promote better extraction and performance. In this context, the aqueous preparation method showed inferior removal rates for the evaluated parameters compared to moringa powder and the saline solution [41].

Similar results were observed in a previous study that compared different preparation methods of moringa-based biocoagulants. The aqueous solution achieved 35.5% removal of apparent color and 60.5% of turbidity. In comparison, the moringa powder increased removal efficiency by 44.3% for color and 23.5% for turbidity concerning the aqueous solution, reaching 79.8% and 84.0%, respectively. The saline solution showed even higher performance, with removal increases of 47.4% and 28.8% based on the aqueous solution, achieving removal rates above 80.0% for both parameters [28]. These findings reinforce the inferiority of the aqueous method compared to the powder and saline methods for using moringa as a natural coagulant in the treatment of raw surface waters.

Based on the contour plots (see Figures 4–9), the following combinations of dosage and sedimentation time were defined as optimal points for moringa seed-based coagulants: 80 mg·L⁻¹ in 20 min for the powder; 40 mg·L⁻¹ in 30 min for the saline solution; and 40 mg·L⁻¹ in 40 min for the aqueous solution. The performance differences between the moringa oleifera biocoagulant preparation methods are primarily associated with the solubility of the coagulant proteins and the ionic strength of the medium. In powdered coagulant, the active compounds are released gradually during the process, favoring rapid floc formation and, consequently, shorter sedimentation times. In saline solution, the addition of NaCl increases protein solubility and charge neutralization, promoting the formation of larger, more stable flocs with lower dosages. This superiority is related to the higher concentration of active proteins and the presence of chloride ions, which act as supporting electrolytes. These ions reduce the thickness of the electrical double layer surrounding the colloidal particles, facilitating their convergence and flocculent aggregation. In contrast, in aqueous solution, the low solubility of proteins in distilled water limits the coagulant's action, resulting in the formation of smaller, less dense flocs, requiring longer sedimentation times to achieve satisfactory efficiencies [10,21,41,42].

3.2. Conventional Water Treatment

Clarification with the three coagulants greatly reduced apparent color and turbidity, using the three coagulants, with the subsequent filtering, overall improving water quality. Nevertheless, the removals by seed powder and saline solution greatly overcame those of the aqueous solution. The only chemical parameter that increased was the chloride concentration for the saline solution. Despite clarification and filtering, the microbiological parameters remained high (Table 1).

Moringa powder promoted significant reductions in apparent color and turbidity; however, the final values did not meet the limits established by Ordinance GM/MS n°. 888/2021 [31], even after filtration. The saline solution showed better performance, with an apparent color of (8.67 ± 1.53) uH and turbidity only 0.9 NTU above the permitted level after filtration. The filtration after the aqueous solution further removed 32.1% in apparent color removal and 20.7% in turbidity, which are also above the established limits.

Chloride levels remained below the legal limit of 250 mg·L⁻¹ in all preparation methods. In the saline solution, chloride increased significantly due to the NaCl used, but values stayed within the allowed limit.

Table 1. Quality parameters of the water and their reductions ($\downarrow$) through clarification with the different moringa biocoagulants, followed by filtering.

Quality Parameter	Raw Water	Powder		Saline Solution		Aqueous Solution		Maximum Value (GM/MS n°. 888/2021)
		Clarified	Filtered	Clarified	Filtered	Clarified	Filtered	
Apparent color (uH)	797.67 ± 1.53	59.00 ± 9.17	23.50 ± 3.51	66.00 ± 1.73	8.67 ± 1.53	650.33 ± 8.14	394.0 ± 1.52	15.0
$\downarrow$ (%)	-	92.6 ± 1.15	97.0 ± 0.44	91.7 ± 0.22	98.9 ± 0.19	18.5 ± 1.02	50.6 ± 0.19	-
Turbidity (NTU)	94.33 ± 2.08	20.77 ± 0.38	9.15 ± 1.19	19.43 ± 0.59	5.09 ± 0.44	64.57 ± 1.91	45.03 ± 0.50	5.0
$\downarrow$ (%)	-	78.0 ± 0.40	90.3 ± 1.26	79.4 ± 0.62	94.6 ± 0.46	31.6 ± 2.03	52.3 ± 0.53	-
Cl ⁻ (mg·L ⁻¹)	22.20 ± 5.33	6.47 ± 0.83	4.00 ± 2.08	156.10 ± 39.71	142.23 ± 16.49	13.27 ± 1.91	10.63 ± 2.69	250.0
$\downarrow$ (%)	-	70.9 ± 3.75	85.7 ± 9.38	0.0 ± 178.85	0.0 ± 74.2	40.2 ± 8.62	52.1 ± 12.10	-
NH ₃ (mg·L ⁻¹)	1.39 ± 0.01	0.62 ± 0.13	0.22 ± 0.01	0.26 ± 0.02	0.22 ± 0.01	0.75 ± 0.01	0.65 ± 0.01	1.5
$\downarrow$ (%)	-	55.0 ± 9.20	84.1 ± 0.72	81.2 ± 1.44	84.4 ± 0.42	46.1 ± 0.83	53.1 ± 0.72	-
Al (mg·L ⁻¹)	0.74 ± 0.43	0.01 ± 0.01	0.00 ± 0.00	0.01 ± 0.02	0.01 ± 0.01	0.03 ± 0.03	0.02 ± 0.00	0.2
$\downarrow$ (%)	-	99.1 ± 1.20	99.6 ± 0.59	98.2 ± 2.49	99.1 ± 0.88	96.1 ± 3.57	97.0 ± 0.51	-
Cu (mg·L ⁻¹)	0.16 ± 0.05	0.07 ± 0.02	0.00 ± 0.02	0.03 ± 0.02	0.05 ± 0.01	0.02 ± 0.02	0.01 ± 0.02	2.0
$\downarrow$ (%)	-	56.3 ± 12.50	93.8 ± 10.83	81.3 ± 12.5	70.8 ± 3.61	85.4 ± 13.01	93.8 ± 10.83	-
Fe (mg·L ⁻¹)	1.84 ± 0.24	1.19 ± 0.10	0.76 ± 0.02	0.26 ± 0.04	0.09 ± 0.01	0.65 ± 0.32	0.61 ± 0.08	0.3
$\downarrow$ (%)	-	35.2 ± 5.53	59.0 ± 1.26	85.8 ± 1.96	95.1 ± 0.54	64.6 ± 17.45	66.8 ± 4.11	-
Mn (mg·L ⁻¹)	0.49 ± 0.01	0.12 ± 0.01	0.02 ± 0.01	0.00 ± 0.00	0.00 ± 0.00	0.13 ± 0.02	0.10 ± 0.00	0.1
$\downarrow$ (%)	-	76.0 ± 1.90	94.2 ± 1.67	100.0 ± 0.00	100.0 ± 0.00	73.7 ± 4.35	79.1 ± 0.31	-
<i>E. coli</i> (NMP/100 mL ⁻¹)	>2419.6 ± 0.00	>2419.6 ± 0.00	622.1 ± 113.4	>2419.6 ± 0.00	1613.0 ± 347.2	>2419.6 ± 0.00	>2419.6 ± 0.00	Absent in 100 mL
$\downarrow$ (%)	-	(-)	>75.3 ± 4.69	(-)	>33.3 ± 14.35	(-)	(-)	-
pH	7.41 ± 0.13	7.38 ± 0.12	7.40 ± 0.06	7.33 ± 0.08	7.11 ± 0.13	7.36 ± 0.09	7.37 ± 0.04	6.0–9.5

(-) the reading exceeded the equipment capacity; $\pm$ standard deviations.

Ammonia met the potability standards after clarification in all preparation methods, with additional removal of 29.1% after filtration in the powder form, 3.2% in the saline solution, and 7.0% in the aqueous solution.

pH remained stable across all moringa preparation methods, confirming that its use does not significantly alter this parameter, as indicated by previous studies [25,28,40,44].

One of the advantages of natural coagulants, such as those derived from moringa, is precisely their effectiveness regardless of pH variations, in addition to their tendency to maintain the pH of the treated water virtually unchanged, unlike inorganic coagulants [45]. This behavior is particularly beneficial in subsequent treatment steps, such as chlorination, since the neutral pH commonly observed after the use of moringa is in the ideal range between 6.5 and 7.5 for the formation of hypochlorous acid (HOCl), the most effective disinfectant [46].

The aluminum met the limits established by current legislation already in the clarification stage, regardless of the preparation method, presenting removals of $(99.1 \pm 1.20)\%$ for the powder, $(98.2 \pm 2.49)\%$ for the saline solution, and $(96.1 \pm 3.57)\%$ for the aqueous solution.

Copper, whose initial concentration was already within the limits established by Brazilian legislation, was removed by $(56.3 \pm 12.50)\%$ during the clarification stage using

the powder preparation. The saline solution reduced the copper content by $(81.3 \pm 12.50)\%$, while the aqueous solution achieved $(85.4 \pm 13.01)\%$ removal.

In the powder preparation, iron did not reach the legal limit of $0.3 \text{ mg}\cdot\text{L}^{-1}$, even with an additional removal of 23.8% after filtration. The saline solution met the limit already at the clarification stage, with a removal of $(85.8 \pm 1.96)\%$. In the aqueous solution, despite a $(66.8 \pm 4.11)\%$ removal after filtration, iron levels remained above the permitted limit.

Manganese in the powder preparation reached the limit for human consumption after an additional 18.2% removal through filtration. In the saline solution, it was completely removed during the clarification stage. In the aqueous solution, the final removal of $(79.1 \pm 0.31)\%$ after filtration brought the parameter within the limits established by Brazilian legislation.

The efficiency of metal removal varied among the analyzed elements and the different preparation methods of the biocoagulant. Aluminum removal was particularly high across all methods, a result attributed to the strong affinity of moringa proteins for trivalent ions [47]. The powder and saline solution forms showed notable performance in heavy metal removal, standing out as promising alternatives for the treatment of contaminated water [48–50]. Although less effective, the aqueous solution also demonstrated the ability to reduce metal concentrations, in line with findings from previous studies [51,52].

Due to the high concentration of total coliforms in the raw water, which exceeded the equipment's reading limit, it was not possible to evaluate the antimicrobial efficacy of moringa in any of the three preparation methods, despite its potential already demonstrated in previous studies [20,53]. Performing dilutions could have allowed for a more accurate analysis.

A reduction in *E. coli* was observed only after filtration, with $(>75.3 \pm 4.69)\%$ removal for the powder method and $(>33.3 \pm 14.35)\%$ for the saline solution, while no removal was detected at any stage for the aqueous solution. Previous studies have reported removal rates of up to 85.9% during the clarification stage of surface water treatment in Nigeria [20]. Other studies highlight the effectiveness of moringa in improving the microbiological quality of water, although complete elimination of microorganisms such as *E. coli* is not always achieved [54]. In this context, proper dilution of samples is essential to enable accurate evaluation of *E. coli* removal during the clarification process.

However, some factors can interfere with effective microbiological action, such as initial water turbidity, strongly associated with seasonality, which directly influences removal efficiency [55]. Furthermore, whole seeds contain, in addition to the cationic proteins of interest, lipids and carbohydrates that can be released during treatment, resulting in dissolved organic carbon (DOC), which can favor microbial growth and the formation of disinfection byproducts [17]. These factors reinforce the need to combine the use of moringa with complementary disinfection steps to ensure the microbiological safety of the treated water, as well as the evaluation of the formation of trihalomethanes [29].

4. Conclusions

The dosage and sedimentation time influence the efficiency of water treatment with moringa, with the best results obtained using $80 \text{ mg}\cdot\text{L}^{-1}$ at 20 min for the powdered method, $40 \text{ mg}\cdot\text{L}^{-1}$ at 30 min for the saline solution, and $40 \text{ mg}\cdot\text{L}^{-1}$ at 40 min for the aqueous solution.

The parameters chloride and copper already had concentrations below the limits established by Brazilian legislation in the raw water, before treatment. In the powdered moringa method, ammonia and aluminum met legal standards at the clarification stage, while filtration also allowed manganese to fall within the permitted limits. In the saline solution method, ammonia, aluminum, iron, and manganese met potability standards

during clarification and filtration, enabling the apparent color to comply with legal standards as well. In the aqueous solution method, clarification was effective for ammonia and aluminum, and filtration brought manganese into compliance with current legislation. The pH did not show significant variations in the results after treatment in any of the three preparation methods.

Regarding microbiological parameters, the removal of total coliforms and *E. coli* was insufficient across all methods and stages, highlighting the need for disinfection to ensure water potability.

It was observed that the results obtained with the aqueous solution were inferior to those obtained with the powder and saline solution methods. It was observed that the results obtained with the aqueous solution were inferior to those obtained with the powder and saline solution methods. The removal efficiencies in the clarification stage for the parameters apparent color, turbidity, chloride, ammonia, aluminum, copper, iron, and manganese, using the aqueous solution, were, respectively, 74.1%, 46.4%, 30.7%, 8.9%, 3.0%, 0.0%, 0.0%, and 2.3% lower compared to the powder method; and 73.2%, 47.8%, 0.0%, 35.1%, 2.1%, 0.0%, 21.2%, and 26.3% lower compared to the saline solution method.

Nevertheless, moringa proved to be an effective coagulant in the removal of various quality parameters, standing out as a promising and eco-friendly alternative for water treatment. Its use offers several environmental and economic advantages, especially in areas where access to conventional water treatment resources is limited.

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