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Turbidity Removal Performance of Selected Natural Coagulants for Water Treatment in Colombian Rural Areas

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Abstract

Despite the recognized efficiency of natural coagulants, their widespread adoption in the water treatment industry remains low. Our study evaluates the effectiveness of three natural coagulants—Moringa Oleifera, Yausa (Abutilon Insigne Planch), and Breadfruit (Artocarpus Altilis)—in reducing water turbidity levels of 40–50 NTU. Among these, two are native plant species potentially applicable in rural Colombian areas, where there are evident disparities in water infrastructure. This research contributes to the development of these coagulants, exploring their integration with existing water treatment methods, determining their optimal concentrations, and efficiencies in turbidity removal. Our findings reveal significant turbidity removal efficiencies: 88.9% for Moringa Oleifera, 83.3% for Yausa, and 67.2% for Breadfruit. These results indicate the feasibility of these agents as sustainable replacements for traditional chemical coagulants, exhibiting a level of effectiveness alike to that observed in Moringa Oleifera. However, challenges in practical implementation and sustainability, covering technical, environmental, economic, and social aspects, are notable obstacles. The aim of this study is to not only demonstrate the effectiveness of these natural coagulants but also to encourage their broader acceptance and integration into sustainable water treatment practices incorporating two unstudied plant species, such as Yausa and Breadfruit, furthering research to overcome existing challenges.

Keywords: Water Treatment; Natural Coagulants; Moringa Oleifera; Yausa; Turbidity Removal; Color Removal; Sustainability.

1. Introduction

Access to safe drinking water is a fundamental human right, essential for public health and sustainable development [1]. A study conducted by Boretti and Rosa [2] on the United Nations World Report on Water Development (2019) indicates that global water demand is steadily increasing, driven by growing industrial and domestic needs. Projections suggest a 20–30% rise in water usage by 2050, exacerbating the challenges of ensuring adequate water availability and quality. Currently, about 30% of the global population lacks access to safe drinking water, underscoring the urgency for innovative water treatment solutions [3].

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In developing countries, particularly in rural areas, where over 80% of small family farms reside, the absence of proper water infrastructure significantly contributes to poverty and food insecurity [4]. These regions, vital for global food production, are hindered by inadequate water and sanitation services, exacerbating socioeconomic disparities [5]. Improving water quality and availability in rural areas is critical for enhancing living conditions and economic development [6]. Public water systems in these areas face challenges such as rising populations, operational inefficiencies, and limited coverage, further intensifying the water crisis. Thus, there is a need for sustainable, cost-effective water supply initiatives that are sensitive to the socio-economic realities of these populations [7].

The Global Water Resources Report [2] highlights the socio-economic advantages of expanded utility coverage, emphasizing the positive cost-benefit ratio of drinking water projects. This underscores the need for affordable water supply solutions, especially in rural contexts, with pricing strategies that are sensitive to the varied socio-economic groups within these communities. In alignment with these findings, nature-based solutions emerge as a promising avenue [8]. They are actions that protect, sustainably manage, and restore natural and modified ecosystems to address societal challenges effectively and adaptively, benefiting both people and nature. These solutions harness the resilience of healthy ecosystems to safeguard human communities, optimize infrastructure, and ensure a stable and biodiverse future. In this context, natural coagulants represent a viable, nature-based solution for water treatment. Derived from natural sources like plants, they are readily accessible, cost-effective, simple to apply, biodegradable, non-toxic, environmentally friendly, efficient, and result in lower sludge volumes [9]. This makes them particularly suitable for rural areas, where economical and eco-sensitive water treatment methods are essential.

In Latin America, the challenge of providing optimal water quality in rural areas is particularly acute [10]. For instance, in Colombia, despite advancements in urban water supply, rural areas lag significantly behind [11]. The National Institute of Health (2020) reports that only 42% of rural Colombians have access to safe drinking water [12]. This situation calls for effective, location-specific water treatment solutions. Conventionally, water purification relies on chemical coagulation and flocculation. However, concerns about the health risks and environmental impact of chemical coagulants like aluminum sulphate have prompted the search for sustainable alternatives [13]. Natural coagulants, derived from plants and seeds, present a promising solution. Their cost-effectiveness, environmental friendliness, and operational efficiency make them suitable for water treatment in resource-limited settings [14].

This study evaluates the efficacy of three natural coagulants – Moringa oleifera (M. Oleifera), which is found in various geographic locations worldwide, and Yausa (Abutilon insigne Planch) and Breadfruit (Artocarpus Altilis), both native to Colombia – in the vital task of reducing water turbidity. This process is crucial for ensuring the provision of clean, safe drinking water, a key factor in protecting public health and preserving ecological system integrity [14]. These plants, while native to specific geographic areas and integral to local cultural and industrial practices, present a viable and sustainable method for water treatment, particularly in rural communities [15, 16].

This research includes a comparative evaluation of various coagulants to establish their respective efficacies. Special emphasis is placed on Yausa (Abutilon insigne Planch) and Breadfruit (Artocarpus Altilis), as these native species are expected to significantly enhance water quality in rural areas. The findings from this study are alleged to make a substantial contribution towards the advancement of novel, economical, and eco-friendly water treatment technologies.

The primary goal of this research is to pioneer a novel domain of inquiry by investigating the coagulation properties of two Colombian native plant species, Yausa (Abutilon Insigne Planch) and Breadfruit (Artocarpus altilis), alongside the extensively studied Moringa Oleifera, for water treatment specifically for water turbidity reduction. Employing natural coagulants in water treatment represents a pivotal shift towards sustainable and environmentally conscious practices [14]. This strategy is especially relevant in rural areas of developing countries, where conventional treatment methods may not be feasible [17]. Investigating and utilizing Yausa (Abutilon insigne Planch) and Breadfruit (Artocarpus Altilis) of natural coagulants in these regions offers the potential to create water treatment solutions that are both environmentally and economically sustainable. This approach not only ensures access to purified water but also aids in conserving local ecosystems and fostering economic development, ultimately bolstering public health, and strengthening the resilience of these communities [18].

2. Outlook of the Potential of Natural Coagulants for Water Treatment

Providing clean and safe water is a critical global challenge, essential for sustaining life and fostering societal development. In the technology portfolio of effective water treatment strategies, coagulation plays a vital role in removing suspended solids, colloidal particles, and organic matter [14]. While traditional metal-based coagulants have proven effective, their drawbacks, like chemical sludge production and adverse environmental impacts, have spurred the exploration of alternative, eco-friendly solutions [19]. A diverse range of sustainable coagulants, including plant-based extracts, biopolymers, and natural organic coagulants, are explored, highlighting their unique coagulation mechanisms and their promising potential in water purification [20, 21].

Water treatment involves a combination of physical, chemical, and biological processes to remove impurities, contaminants, and pathogens from water, making it safe for various applications. Coagulation, as one of the chemical treatment methods, plays a crucial role in the overall water treatment process. It involves the addition of coagulants to destabilize suspended particles and colloids, facilitating their aggregation into larger flocs for subsequent removal. Table 1 presents a summary of different methods for water treatment that utilize coagulants.

Table 1. Coagulant-based methods for water treatment

Method	Description	Source
Conventional Coagulation	The most common method using metal-based coagulants (e.g., alum, ferric chloride) to form positively charged metal hydroxide complexes, causing particles to clump.	[19]
Enhanced Coagulation	Higher coagulant doses are used to achieve more effective removal of specific contaminants like natural organic matter, dissolved organic carbon, and trace elements.	[22–24]
Pre-Coagulation	Coagulants are added to raw water before other treatment processes to improve particle destabilization, reduce turbidity and color, and enhance overall performance.	[25]
In-Line Coagulation	Coagulants are directly injected into the water stream using specialized systems, enhancing efficiency, and reducing chemical consumption in larger treatment plants.	[20]
Sustainable Coagulants	Eco-friendly alternatives like plant-based extracts, biopolymers, and natural organic coagulants are explored to reduce environmental impact compared to metal-based options.	[26]
Ballasted Flocculation	Coagulated water is mixed with heavy particles (ballast) to encourage the formation of larger, denser flocs, enhancing sedimentation and filtration efficiency.	[27]
Membrane Coagulation	An innovative approach combining coagulation and membrane filtration, where coagulants improve membrane performance, reducing fouling and improving water quality.	[28-30]

Chemical coagulants are the most conventional products employed in water treatment processes to facilitate the aggregation and precipitation of suspended particles, colloids, and other impurities. However, their environmental drawbacks have led the utilization of natural coagulants into water treatment protocols.

2.1. Natural Coagulants

Natural coagulants have garnered increasing attention as eco-friendly alternatives to traditional chemical coagulants in the field of water treatment. Natural coagulants, derived from plant-based extracts, biopolymers, and organic materials, present promising opportunities for enhanced water treatment while mitigating adverse ecological effects. As global concerns for environmental preservation and sustainable resource management intensify, understanding the merits and limitations of natural coagulants becomes crucial in adopting a greener and healthier future for water treatment practices [19, 20].

Table 2 illustrates the turbidity removal efficiency of the studied natural coagulants, showcasing their performance in both potable water and wastewater samples. The results shown in the table were derived from experimental trials conducted in the laboratory at the Universidad Mariana.

Table 2. Common natural coagulants used for water treatment in Colombia

Coagulant	Turbidity removal efficiency (%)
Moringa Oleifera	80.1±19.8
Opuntia ficus indica	86.1±12.3
Potato	87.1±7.3
Cassia alata	81.5±13.4
Breadfruit (Artocarpus Altilis)	62.5±11.5
Coffee	81.8±17.6
Zea may	66.9±19.1
Abutilon insigne Planch	65.5±11.2

The consideration of natural coagulants as a replacement for conventional chemical coagulants embodies a paradigm shift towards more sustainable and ecologically sound water treatment practices. The unique attributes of natural coagulants align with the goals of existing water treatment, encompassing both operational efficiency and environmental stewardship. The main attributes of natural coagulants are presented in Table 3.

Table 3. Comparative analysis of natural coagulant properties

Natural coagulant attribute	Observations	Reference
Eco-Friendliness	Biodegradable and pose minimal risk to the environment. Unlike chemical coagulants, they do not introduce synthetic compounds into water systems, reducing the potential for long-term ecological disruptions.	[20]
Reduced Chemical Residue	The chemical footprint is lower than chemical coagulants, ensuring water quality without compromising safety.	[14, 21]
Health Considerations	Their organic nature and reduced chemical content make them a safer choice, particularly in scenarios where treated water is intended for consumption or direct human contact.	[31, 32]
Cost-Effectiveness	Their sustainable procurement and processing can result in lower economic outlays, aligning with budget considerations in water treatment projects.	[33]
Enhanced Environmental Compatibility	They minimize the introduction of extraneous substances into water systems, preserving water quality and mitigating downstream environmental disturbances.	[14-21]

3. Material And Methods

3.1. Selected Natural Coagulants for Turbidity Removal

This research study explores the turbidity removal efficiency of three natural coagulants: Moringa oleifera, Yausa (Abutilon Insigne Planch), and Breadfruit (Artocarpus Altilis). These plant-based coagulants were carefully selected not only for their proven turbidity removal capabilities but also for their abundant presence within Colombian territory. Specifically, Yausa and Breadfruit, native to Colombia, are under-researched in this context. Preliminary experiments in our research facility, have indicated their potential as effective coagulants, warranting further exploration in this study.

Figure 1 provides an insight of two natural coagulants native to two geographical zones in the department of Nariño in Colombia: Yausa and Moringa. Yausa and Breadfruit species studied are native to the Pacific and Andean regions. Yausa (Abutilon Insigne Planch) finds application in the sugar industry of the Andean region of the Nariño department, especially in Sandoná city, to coagulate certain products in the sugar extraction process; however, this mucilaginous plant has not been evaluated in water treatment, especially in turbidity removal. Breadfruit (Artocarpus Altilis), native to the Pacific region, especially in Tumaco City, is utilized for the preparation of traditional local dishes. The experimental analysis was conducted in the laboratories of Mariana University in Pasto, Nariño.

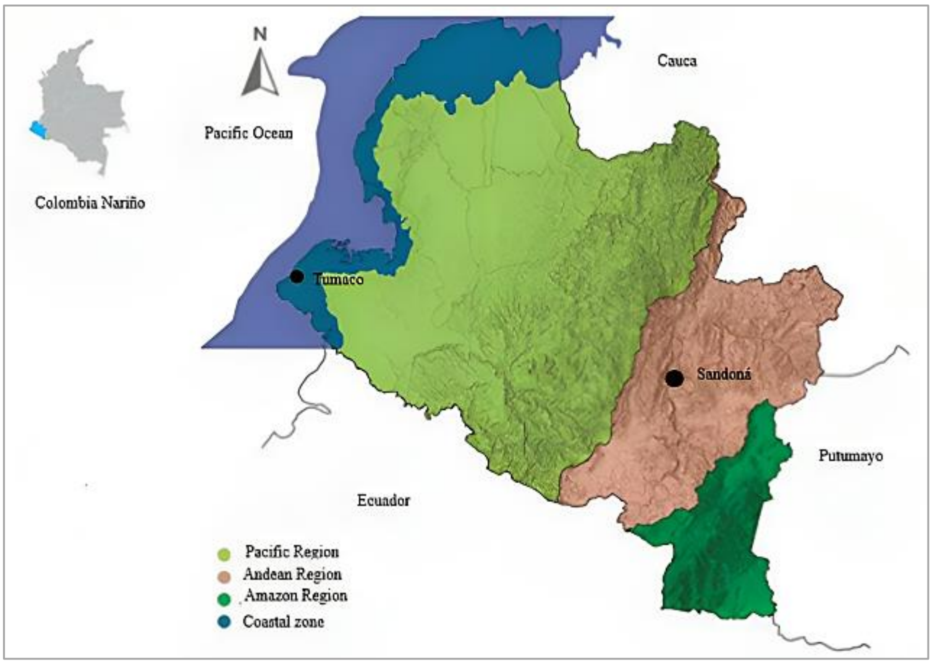

Figure 1. Geographic Distribution of the Studied Native Coagulant Species

3.1.1. Moringa Oleifera

Moringa Oleifera, a fast-growing tropical tree, has garnered considerable attention as a promising natural coagulant for water treatment applications. The seeds of Moringa oleifera contain cationic proteins and polysaccharides that aid in destabilizing suspended particles and colloids in water, promoting their aggregation into larger flocs for efficient removal. As a readily available and sustainable resource, M. Oleifera offers an eco-friendly alternative to traditional chemical coagulants, addressing environmental concerns and resource scarcity [8, 32].

3.1.2. Yausa (Abutilon Insigne Planch)

As a mucilaginous plant native to Colombia, its widespread availability ensures a more economical and convenient sourcing process. Leveraging its local abundance, this study endeavors to evaluate the viability of Yausa as a natural coagulant, aiming to harness its organic properties to enhance water treatment practices. Yausa (Abutilon insigne Planch) has demonstrated remarkable turbidity removal efficacy in the clarification of sugarcane juice, making it a promising candidate for water treatment applications [33]. Yausa offers the advantage of being easily biodegradable, contributing to a more environmentally friendly handling of sludge produced during the treatment process. The reduced environmental impact aligns with the growing global emphasis on adopting eco-friendly solutions for water purification.

3.1.3. Breadfruit (Artocarpus Altilis)

The breadfruit plant (Artocarpus altilis) is a tropical tree known for its starchy and nutritious fruit. It is native to the Pacific Islands but has been cultivated in various tropical regions around the world. The breadfruit has long been utilized as a staple food source due to its versatility and high carbohydrate content. Various parts of the breadfruit plant, including the latex from its stems, have been recognized for their coagulation properties. The latex contains proteolytic enzymes that can effectively coagulate suspended particles and impurities in water, making it a natural coagulant solution for water treatment processes. This coagulation ability is attributed to the enzymes' capacity to aggregate and bind fine particles together, forming larger flocs that can be more easily removed from water [34].

3.2. Extraction and Preparation of Coagulant Solution

Stock solutions were prepared following the protocol proposed by Quezada Moreno et al. [35]. For the M. Oleifera solution, a mixture of 50g of M. Oleifera seed powder and 1 Liter of saline solution was prepared, resulting in a weight/volume ratio of (50g/1000ml). The solution was subjected to thorough stirring for a duration of 1 hour, followed by filtration using a 0.45mm filter to obtain a clear liquid extract, which was then set aside for precise dosing during the trials.

As for the Yausa (*Abutilon Insigne Planch*) coagulant solution, it was formulated by combining 0.250 g of Yausa leaves with 1 Liter of water. The mixture underwent a blending process and was then stirred for 1 hour. After this, the solution was subjected to another round of filtration to yield a clarified liquid extract, which was carefully drawn off for accurate dosing in the experimental setup.

In the case of the Breadfruit (*Artocarpus altilis*) coagulant solution, formulation entailed the mixture of 25g of Breadfruit with 1 Liter of water. The resulting mixture underwent a thorough blending procedure, followed by a stirring duration of 1 hour. By adhering to the well-established procedure proposed by Quezada Moreno et al. [35], we ensure the reliability and comparability of our results.

Figure 2 illustrates a comprehensive flow diagram detailing the methodology employed for the extraction and preparation of the three studied natural coagulants: Moringa oleifera, Yausa (Abutilon Insigne Planch), and Breadfruit (Artocarpus Altilis). This diagram summarizes each step of the process, from the initial collection of raw plant materials through to the final preparation of the coagulants. The flowchart provides a clear and systematic overview of the procedures utilized, ensuring reproducibility and consistency in the extraction and preparation phases across all three coagulants.

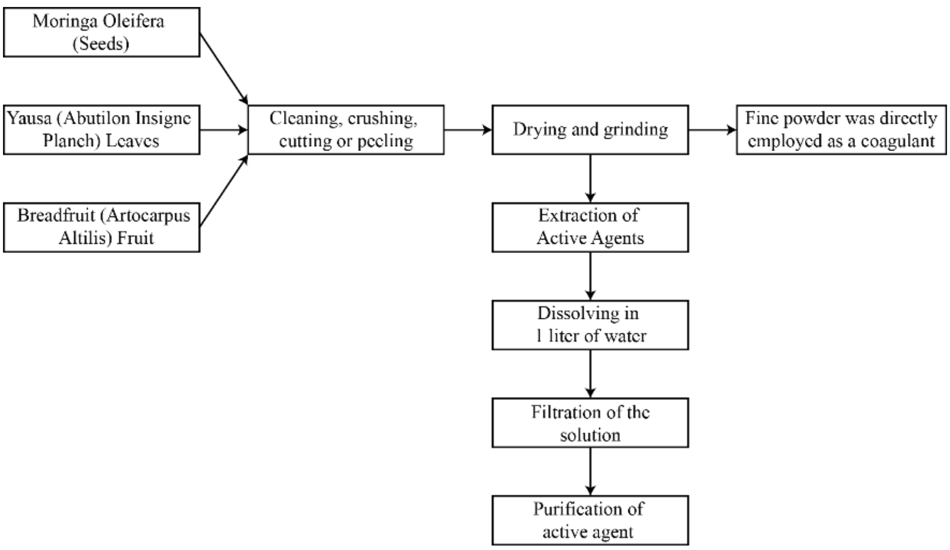

Figure 2. Scheme of selected natural coagulant extraction and preparation methodology

3.3. Characteristics of Untreated Water for Treatment

For the assessment of the M. Oleifera coagulant, water samples were collected from the Santa Helena brook in Medellin, Colombia. Physicochemical parameters, including pH, color and turbidity were directly measured to characterize the raw water. In the case of the Yausa coagulant, a synthetic solution with a comparable turbidity level (40 NTU) to that of the Santa Helena brook was prepared. The synthetic solution was then subjected to evaluation, where physicochemical parameters such as pH, color and turbidity were directly measured. For the breadfruit coagulant, a synthetic solution was formulated considering a turbidity of 37 NTU. Subsequently, an assessment of this synthetic solution was conducted, encompassing the direct measurement of pH, color and turbidity. Consolidated results from the untreated water are presented in Table 4.

Table 4. Physicochemical characterization of test fresh water and synthetic effluent samples

Parameter	Units	Santa Helena Brook	Synthetic effluent Yausa trial	Synthetic effluent Breadfruit trial
pH	-	7.6	8.1	8.0
Turbidity	NTU	47.1	40	37
Color	PCU	220	44	10

3.4. Optimizing Coagulant Dosage Optimization for Enhanced Treatment Efficiency

To determine the optimal dosage and assess the efficiency of turbidity removal, the standard jar test equipment was employed, following ASTM D2035 and the Colombian method NTC 3930. This bench-scale testing procedure replicates the coagulation/flocculation and sedimentation process, allowing for precise evaluation of natural coagulants' performance. The 6-beaker Jar test apparatus was utilized, with each jar filled with 1 Liter of water. For Moringa coagulant, varying volumes of 25, 50, 77, 100, 125, and 150 ml were evaluated. For Yausa coagulant, volumes of 2, 5, 10, 20, 40, 60, and 80 ml were tested, while for Breadfruit (*Artocarpus altilis*) coagulant solution, volumes of 100, 110, 120, 130, 140, and 150 ml were evaluated. Each experiment was conducted in triplicate, and the beakers were subjected to agitation at different mixing times and speeds: rapid mixing at 100 rpm for 1 minute, followed by slow mixing at 40 rpm for 15 minutes. After agitation, the suspended solids were allowed to settle for 15 minutes.

For turbidity analysis, water samples were pipetted out of the first beaker and transferred to sample vials, ensuring the absence of air bubbles. The sample vials were then placed in calibrated portable instruments, utilizing the HANNA 93703 (infrared LED) turbidity meter for turbidity readings. The direct measurement method was employed for turbidity, ensuring accurate and reliable results.

4. Results

Table 5 presents an analytical overview of experimental trials conducted to assess the turbidity removal efficiency of three different natural coagulants. This table outlines how varying doses and concentrations of these coagulants influence the turbidity reduction in water samples, in which it is correlated the specific coagulant quantities with the corresponding decrease in turbidity levels, providing a quantitative understanding of the effectiveness of each coagulant. This data is crucial for determining the optimal dosages required to achieve maximum turbidity removal, thereby enabling a more precise and effective application of these natural coagulants in water treatment processes.

Table 5. Turbidity removal results from different concentration of selected natural coagulants

Coagulant	Initial turbidity (NTU)	Dose (ml)	Concentration (mg/L)	Final turbidity average (NTU)	Turbidity removal average (%)
Moringa Oleifera	47	0.5	31.3	13.2	71.9
		1	62.5	5.2	88.9
		1.5	93.8	5.3	88.7
		2	125	5.3	88.7
		2.5	156.3	6.4	86.4
		3	187.5	6.9	85.3
Yausa (Abutilon Insigne Planch)	40	8	2	7.9	80.3
		20	5	7.0	82.5
		40	10	6.7	83.3
		80	20	6.8	83.0
		160	40	7.3	81.8
		240	60	7.5	81.3
		320	80	7.3	81.8

Breadfruit (Artocarpus altilis)	37	100	5000	13.3	64.0
		110	5500	12.3	66.6
		120	6000	12.2	67.1
		130	6500	12.5	66.1
		140	7000	12.2	67.2
		150	7500	12.2	66.9

The data clearly show evidence of the optimal doses and concentrations of coagulants for effectively reducing water turbidity. The findings thus serve as a critical step towards the potential adoption and application of these coagulants in water treatment processes, especially in contexts demanding environmentally friendly and cost-effective solutions. This study considers water turbidity as a critical parameter in evaluating water quality, as it directly correlates with the concentration of suspended particulates present. This measurement is essential in assessing water quality by indicating potential health risks and ecological impacts associated with high particulate matter. Turbidity levels, therefore, serve as a vital indicator for water treatment processes, environmental monitoring, and public health assessments, highlighting the necessity of maintaining low turbidity for safe and clean water supply.

In this research study, a series of trials were undertaken to assess the efficacy of three different natural coagulants in turbidity mitigation. In the conducted trials, water samples treated with Moringa Oleifera had an initial turbidity of 47 NTU. In comparison, samples treated with Yausa and Breadfruit had lower initial turbidities of 40 NTU and 37 NTU, respectively. Results from the trials show up the efficacy of Moringa Oleifera in turbidity reduction. When applied at a concentration of 62.5 mg/L (1ml), Moringa Oleifera achieved an 88.9% decrease in turbidity illustrating its potential as an agent for mitigating water turbidity (Figure 3). This level of efficiency is notable, especially in the context of treating waters with high turbidity levels. Furthermore, these findings are in accordance with those reported by Peña-Guzmán & Ortiz-Gutierrez [36], which reinforces the efficacy of Moringa Oleifera as a natural coagulant in water treatment applications.

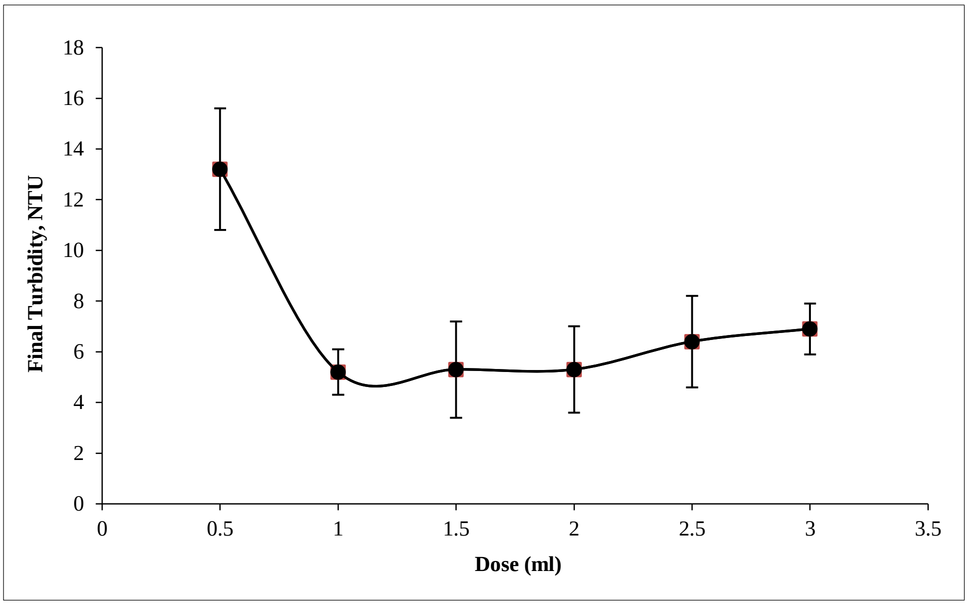

Figure 3. Final turbidity removal from Moringa Oleifera

Results for Yausa (Abutilon Insigne Planch) demonstrated its considerable efficacy in turbidity reduction. As illustrated in Figure 4, the optimal concentration for Yausa was determined to be 10 mg/L (40ml), reaching a turbidity reduction efficiency of 83.3%. This level of effectiveness is significant, suggesting that Yausa could be a highly competent natural coagulant. The ability of Yausa to effectively reduce turbidity at such a low concentration not only underscores its potential as an efficient coagulant but also indicates its suitability for practical application in water treatment processes, particularly in scenarios where minimal intervention is desired for maintaining ecological balance and reducing treatment costs. Quezada-Moreno et al. [35] conducted similar experiments using Yausa (Abutilon Insigne Planch) obtaining similar results on turbidity removal efficiency. Our results are in accordance with those of Garcés et al. [37], in which it was investigated the turbidity removal capabilities of Yausa. Employing a comparable coagulant solution preparation method, their study used a concentration of Yausa, specifically 250 mg/L. In their study, it was found that the optimal dosage for achieving effective turbidity reduction was 70 mg/L, resulting in a turbidity removal efficiency of 79.4%.

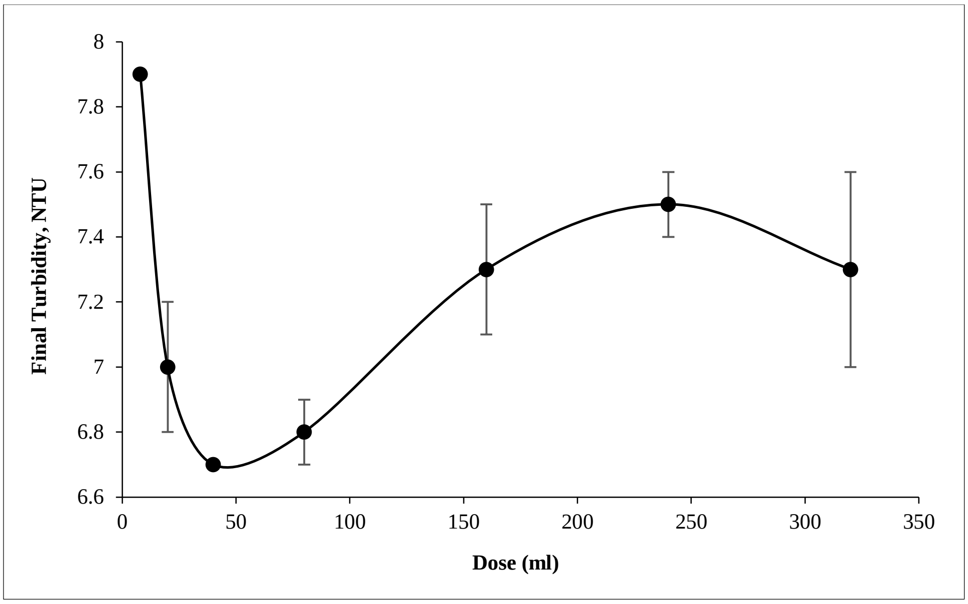

Figure 4. Final turbidity removal from Yausa (Abutilon Insigne Planch)

Figure 5 presents the analysis of turbidity removal using various concentrations of the natural coagulant Breadfruit (*Artocarpus altilis*). The data reveals that Breadfruit reaches its peak effectiveness at a concentration of 7000 mg/L (140ml), where it accomplishes a turbidity removal efficiency of 67.2%. Although the required volume of the Breadfruit coagulant solution for effective turbidity removal is higher compared to Yausa and Moringa Oleifera, its abundant availability in the Nariño region still positions it as a promising coagulant option for water treatment. This local abundance potentially offsets the need for higher volumes, making Breadfruit a viable and sustainable alternative in this geographical context. Its use could contribute to regionally tailored water purification solutions, leveraging local resources to address water quality challenges.

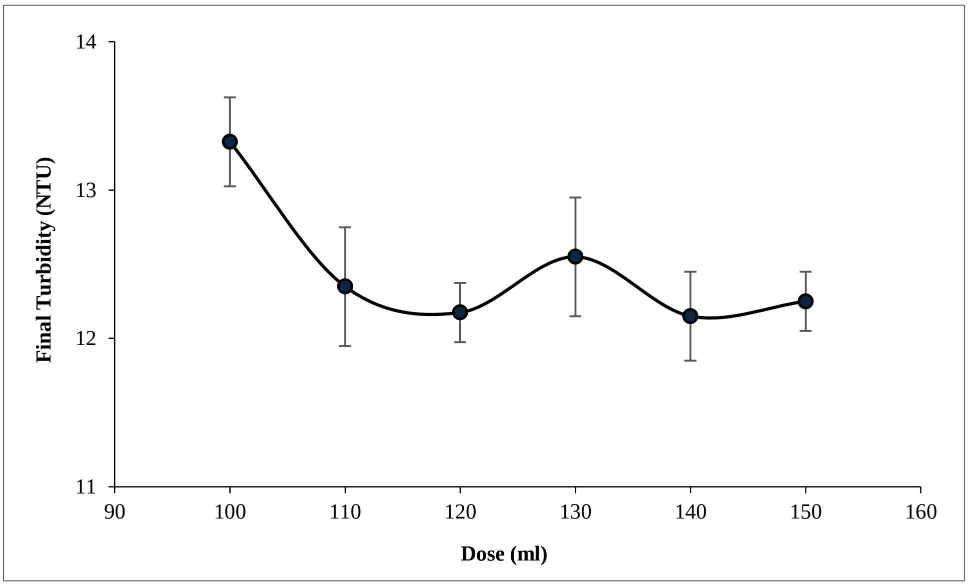

Figure 5. Final turbidity removal from Breadfruit (*Artocarpus altilis*)

The capability of Breadfruit as a coagulant for turbidity removal in water has not been extensively studied, and to our knowledge, this research is among the few documented studies available in the scientific literature. This gap highlights the novelty and significance of our findings, contributing valuable new insights into the potential applications of Breadfruit in water treatment processes.

Figure 6 shows the comparative analysis of turbidity removal efficiencies across different concentrations of all evaluated natural coagulants. The results demonstrate a distinct variation in effectiveness, with Moringa Oleifera (M. Oleifera) achieving the highest turbidity reduction at 88.9%, followed by Yausa and Breadfruit with efficiencies of 83.3% and 67.2% respectively. This figure provides a representation of the coagulants' performance, offering a comprehensive overview of their relative capabilities in reducing water turbidity.

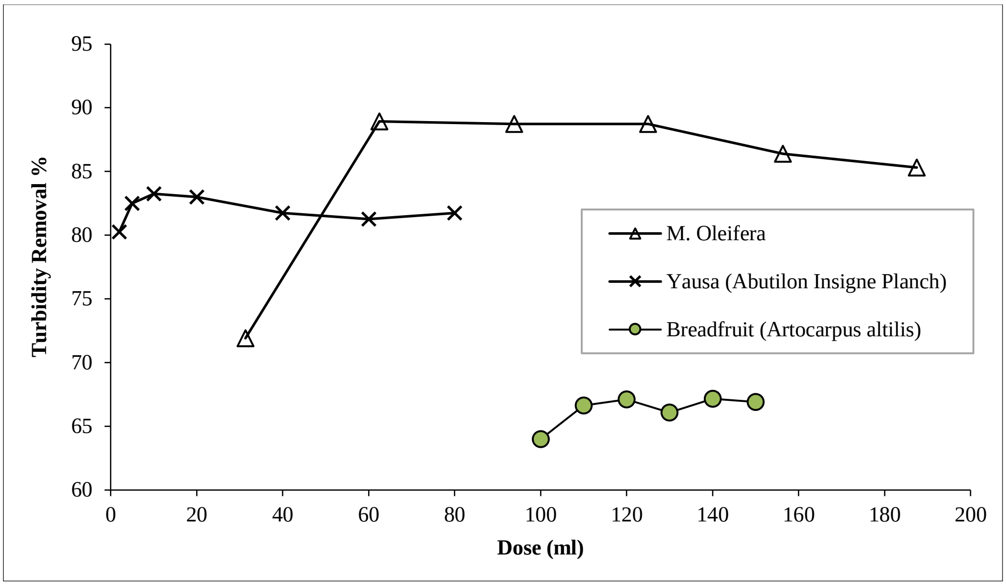

Figure 6. Final turbidity removal percentage from M. Oleifera, Yausa and Breadfruit

The abundance of Yausa and Breadfruit in the Nariño region offers a promising opportunity to attain water turbidity reduction results like those achieved with Moringa Oleifera. Utilizing these naturally abundant coagulants in Nariño could lead to effective and locally adapted water treatment solutions, potentially matching the efficiency of globally recognized coagulants.

5. Discussion

The results of the research study conducted into two unexplored native plant species, Yausa (*Abutilon Insigne Planch*) and Breadfruit (*Artocarpus altilis*), has yielded encouraging results. Extracts from these plants were utilized as coagulants, and their efficacy in reducing water turbidity was assessed. The study found that Yausa achieved a turbidity removal efficiency of 83.3% at a concentration of 10 mg/L, while Breadfruit showed an efficiency of 67.2% at a significantly higher concentration of 7000 mg/L. In comparison, Moringa Oleifera demonstrated an 88.9% efficiency at 10 mg/L. These findings highlight Yausa's potential as an effective water treatment coagulant. However, it is notable that while Breadfruit exhibited promising results, the required concentration of its active component for turbidity removal is substantially greater than that of the other natural coagulants evaluated.

According to the results of Peña-Guzman and Ortiz-Guiterrez [36], natural coagulant Moringa Oleifera, when processed without its shell and using a standardized treatment procedure, achieves a 79.13% turbidity reduction at an initial turbidity of 58 - 62 NTU with an optimal dose of 17.5 mg/L. This substantial decrease in turbidity highlights Moringa's significant effectiveness as a natural coagulant. The high turbidity removal efficacy of Moringa Oleifera is attributed to its cationic proteins, which possess a strong affinity for negatively charged particles and colloids prevalent in turbid water [38]. Further studies, including those by Taiwo et al. [39], have demonstrated that these proteins effectively bind with contaminants, facilitating their aggregation into larger flocs for easier sedimentation and removal. Given its natural abundance and notable turbidity reduction capability, Moringa Oleifera presents itself as a viable option for water purification.

The experimental findings regarding Yausa's (*Abutilon Insigne Planch*) performance as a natural coagulant demonstrate its notable efficiency, positioning it as a viable alternative to chemical coagulants. Achieving a turbidity reduction rate of 83.3% at an optimal concentration of just 10 mg/L, Yausa proves to be not only effective but also highly efficient, especially given the relatively low concentration required for such significant results. Comparable results were reported by Garcés et al. [37], who used a concentration of 250 mg/L for Yausa in their experiments. Adhering to a coagulant solution preparation method like ours, they determined that an optimal dosage of 70 mg/L was effective, achieving a turbidity removal efficiency of 79.4%. The efficacy of Yausa as a coagulant is largely attributed to its mucilaginous composition, which contributes to enhanced coagulation through increased solution viscosity, effective charge interactions, bridge formation between particles, and facilitation of flocculation. These properties underscore Yausa's potential as a sustainable and efficient option in water treatment applications.

Breadfruit, despite achieving a turbidity reduction efficiency of 67.2%, lower compared to Moringa Oleifera and Yausa, still demonstrates potential as an effective coagulant. The requirement of a higher optimal concentration, specifically 7000 mg/L, indicates that Breadfruit's coagulation efficiency may be directly proportional to the concentration used. This suggests that its application might be more appropriate in certain water treatment scenarios where the use of higher coagulant concentrations is both feasible and practical. Based on current literature, there appears to be limited research specifically focusing on the efficacy of Breadfruit in the removal of turbidity from freshwater sources. The coagulation properties of Breadfruit may be linked to the presence of latex in its chemical composition. This latex is rich in proteolytic enzymes, or proteases, known for their pronounced ability to coagulate suspended particles and contaminants in water. Such biochemical attributes suggest Breadfruit's potential utility in water purification, warranting further exploration into its specific mechanisms of action and optimal application conditions [40]. Research conducted by Mótyán et al. [41] provides insights into the functional mechanisms of proteolytic enzymes found in coagulants like Breadfruit. These enzymes interact with proteins in the water, disrupting their stability and thereby reducing the steric and electrostatic barriers that typically inhibit the agglomeration of colloidal particles. Such destabilization promotes the aggregation of these particles. A significant characteristic of these enzymes is their operational adaptability across various pH levels, which makes them suitable for a range of water conditions and obviates the need for pH adjustments during the treatment process [42].

Although all three studied natural coagulants, Moringa Oleifera, Yausa, and Breadfruit, have demonstrated effectiveness in turbidity removal, the variations in their optimal concentrations and efficiency rates indicate potential for diverse applications in water treatment. Yausa, requiring a lower concentration, suggests a reduced need for raw materials, while Moringa Oleifera stands out for its ease of preparation. These distinctions provide a foundation for further research aimed at optimizing the application of these natural coagulants, fitted to the specific requirements of different water treatment scenarios.

6. Conclusions and Recommendations

The increasing interest in research into alternative water treatment methodologies highlights a critical demand for sustainable and eco-friendly practices. The analysis conducted in this study on Moringa Oleifera, Yausa (*Abutilon Insigne Planch),* and Breadfruit (*Artocarpus altilis*) has revealed the promising capabilities of these natural resources as effective natural coagulants. This finding highlights the significant potential of utilizing these plant-based substances in the development of greener water purification strategies.

Moringa Oleifera demonstrated the best coagulation capabilities among the studied natural coagulants, achieving an 88.9% reduction in water turbidity at a concentration of 62.5 mg/L. This performance not only highlights its effectiveness as a natural coagulant but also its practicality, given the tree's rapid growth and ease of cultivation. These attributes suggest a sustainable and reliable source for water treatment applications. As for Yausa, with its notable turbidity reduction rate of 83.3% at a minimal concentration of 10 mg/L, highlights its efficiency and potential as a primary coagulant in water treatment processes. This efficiency, achieved at such a low concentration, indicates its suitability for scenarios requiring effective results with minimal resource utilization. At last, breadfruit's turbidity reduction rate of 67.2%, while lower than the others, provides valuable implications for its use. Given its higher optimal concentration of 7000 mg/L, it may be best suited for settings where such concentrations can be practically and economically managed. Moreover, the abundant presence of breadfruit in certain regions implies that it could be a key resource in developing localized water treatment strategies. These region-specific solutions could leverage the plant's availability to provide cost-effective and regional-adapted approaches to water purification.

Further research is essential to systematically evaluate the studied natural coagulants, extending beyond immediate outcomes to incorporate their long-term effects, potential environmental impacts, and interactions with commonly used chemicals in water treatment processes. A comprehensive understanding is necessary to mitigate any unexpected challenges. Additionally, an in-depth economic analysis is crucial. This analysis should explore cost dynamics, operational expenses, and long-term financial impacts to assess the economic viability of adopting these natural coagulants on a broader scale.

Moreover, establishing a collaborative framework is critical. This framework should foster partnerships among local communities, water treatment facilities, research institutions, and industrial stakeholders. Such collaboration will not only accelerate the research and integration of natural coagulants into existing systems but also promote innovation and a more integrated, community-focused approach to water treatment.

7. Declarations

7.1. Author Contributions

Conceptualization: L.S., E.N., R.S., D.P., E.S., J.C., L.C., G.E., M.B., S.D., and M.L.R.; data curation, L.S., E.N., and M.L.; formal analysis, L.S., E.N., and M.L.; supervision, L.S., E.N., and M.L.; methodology, L.S., E.N., and M.L.; validation, L.S., E.N., and M.L.; writing original draft: L.S., E.N., and M.L.; project administration, L.S., R.S., and E.N.; resources, L.S., R.S., and E.N.; writing—review and editing D.R. and D.A. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

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7.5. Conflicts of Interest

The authors declare no conflict of interest.

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