

## Environment

# Use of agricultural waste: pitaya cladode in sustainable treatment of water for human consumption - part 2

Aproveitamento de resíduos agrícolas: cladódio de pitaia no tratamento sustentável de água para consumo humano - parte 2

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## ABSTRACT

The growing global challenge of access to safe drinking water highlights the need for sustainable alternatives in water treatment. This study evaluated the potential of pitaya cladode (*Hylocereus spp.*) as a natural bio-coagulant, comparing it to aluminum sulfate and *Moringa oleifera*. The methodology involved coagulation tests with varying concentrations and fixed parameters for pH and rapid mixing times, assessing turbidity, apparent color, true color, pH, and Dissolved Organic Carbon (DOC). The results showed that pitaya performed comparably to aluminum sulfate at pH 3, achieving turbidity and apparent color removal rates above 90%, meeting legal standards. At natural pH, pitaya demonstrated efficiency in turbidity removal after filtration, standing out as a promising alternative for less restrictive treatment systems. This study highlights the use of agricultural residues as an innovative and accessible solution for rural communities, contributing to sustainable practices and aligning with the Sustainable Development Goals (SDGs).

**Keywords:** Bio-coagulants; Agricultural waste management; Water quality

## RESUMO

O crescente desafio global de acesso à água potável reforça a necessidade de alternativas sustentáveis no tratamento de água. Este estudo avaliou o potencial do cladódio de pitaia (*Hylocereus spp.*) como biocoagulante natural, comparando-o ao sulfato de alumínio e à *Moringa oleifera*. A metodologia envolveu testes de coagulação com diferentes concentrações e parâmetros fixados para pH e tempos de agitação rápida, avaliando turbidez, cor aparente, cor verdadeira, pH e Carbono Orgânico Dissolvido (COD). Os resultados mostraram que, em pH 3, a pitaia apresentou desempenho comparável ao sulfato de alumínio, com remoções de turbidez e cor aparente superiores a 90%, atendendo aos padrões legais.

Em pH natural, a pitaya demonstrou eficiência na remoção de turbidez após a filtração, destacando-se como uma alternativa promissora para sistemas de tratamento menos restritivos. Este estudo reforça o uso de resíduos agrícolas como solução inovadora e acessível para comunidades rurais, contribuindo para práticas de sustentabilidade e alinhando-se aos Objetivos de Desenvolvimento Sustentável (ODS).

**Palavras-chave:** Biocoagulantes; Gestão de resíduos agrícolas; Qualidade da água

## 1 INTRODUCTION

Pitaya (*Hylocereus spp.*), known as “dragon fruit,” is a cactus native to the tropical and subtropical forests of Central and South America, widely spread in different regions of the world due to its adaptability and resilience in different types of soil and climate Kakade et al. (2022). In addition to its nutritional qualities and bioactive compounds, such as vitamin C, fiber, calcium, and iron, the plant stands out as a potential resource for sustainable technologies on account of its antioxidant and anti-inflammatory properties Shah et al. (2023).

In Brazil, research on pitaya has advanced significantly, with Embrapa developing varieties such as BRS Granada and BRS Minipitaya, adapted for high productivity and resistance. These efforts reflect the plant’s potential for both the fruit market and environmental applications Santos et al. (2022); Faleiro & JJunqueira (2021). The use of pitaya cladode as a bio-coagulant in water treatments is an innovative approach that exploits its bioactive characteristics, offering a sustainable and economically viable alternative to traditional chemical coagulants.

In addition to pitaya, other bio-coagulants, such as chitosan, carboxymethyl chitosan, *Moringa oleifera*, *Cactus opuntia*, *Medicago sativa*, and *Opuntia microdasys*, have been widely studied as sustainable alternatives to traditional metallic coagulants, which pose risks to human health and the environment. Studies show that chitosan and its derivatives, as well as *Moringa oleifera* and *Cactus opuntia*, achieve up to 99% efficiency in removing color and turbidity under varied operating conditions, using lower dosages compared to chemical coagulants, such as aluminum sulfate Santos et

al. (2024); Lima Júnior (2018). These bio-coagulants promote an environmentally safe approach, generating biodegradable and non-toxic sludge in line with the principles of green chemistry and the reuse of agro-industrial waste Kurniawan et al. (2020); Iqbal et al. (2019).

Global water security faces substantial challenges, as highlighted in the 2024 UNESCO Report, which links sustainable water management to peace and prosperity. Approximately 2.2 billion people do not have access to safe drinking water, and 3.5 billion do not have adequate sanitation. Thus, the report highlights the urgency of sustainable and affordable alternatives, especially in areas of highest vulnerability Unesco (2024). In Brazil, meeting the goals of the New Legal Framework for Sanitation, which foresees 99% coverage in water supply and 90% in sewage collection and treatment by 2033, requires innovative solutions that combine efficiency, low cost, and sustainability Instituto Trata Brasil (2024).

In this context, the SDG 6 Report in Brazil: ANA's Vision (2022) highlights the need to universalize water and sewage services, prioritizing the North and Northeast regions, where access to basic services is limited. Initiatives aimed at improving water quality, with integrated management of water resources and community participation, are seen as fundamental to achieving sustainability goals ANA(2022).

This article, a continuation of previous research, seeks to deepen the understanding of the performance of pitaya cladode as a natural coagulant, comparing it to aluminum sulfate and moringa under controlled conditions. The investigation details the physicochemical parameters evaluated, including turbidity, color, and DOC, focusing on Test III, which explores the influence of coagulant concentration. The results aim to reinforce the potential of pitaya cladode as a sustainable and affordable alternative for water treatment, with practical impact, especially for rural communities, contributing to technologies aligned with the Sustainable Development Goals (SDG).

## 2 METHODOLOGY

### 2.1 Objective and Comparative Strategy

The methodology was designed to evaluate the efficiency of pitaya cladode as a natural coagulant, comparing it to aluminum sulfate and moringa, and considering physical-chemical parameters and indicators of water potability. Test III was developed to identify the coagulant concentration that presents the best performance within the pH conditions and rapid agitation time established in Tests I and II (described in the first part of this study). This test focused on analyzing the impact of coagulant concentrations on the water clarification process. The study was conducted in stages as described below:

#### 2.1.1 Raw Water Characterization

The water used in the tests was collected from Itapeva Lagoon and characterized as to turbidity, apparent color, true color, initial pH, and DOC, according to the protocols described in the Standard Methods for the Examination of Water and Wastewater APHA (2023).

#### 2.1.2 Characterization of Coagulants

The qualitative and quantitative characterization of powdered coagulants (pitaya cladode, moringa seed, and aluminum sulfate) were performed using the X-ray Fluorescence Spectrometry (XRF) technique. Considering the scarcity of studies in literature on the pitaya cladode (the focus of this study), it was decided to also characterize it according to its protein content using the Kjeldahl method Malavolta et al. (1997). This analysis complements the data obtained by FRX, allowing a more complete characterization.

### 2.1.3 Preparation and Concentration of Coagulants

The pitaya cladode was collected, washed, dried, and crushed until a homogeneous powder was obtained. The same procedure was conducted for moringa seeds. Aluminum sulfate was used in commercial form. The doses of aluminum sulfate were based on common water treatment practices. The dosages of vegetable coagulants were defined according to previous studies conducted by the group and literature Idris et al. (2013); Hendrawati et al. (2016). Five specific concentrations were selected for each coagulant, aiming at comparative evaluation in different experimental scenarios.

### 2.1.4 Coagulation Assays

The tests were conducted in JarTest, with specific operating conditions for each coagulant, as defined in Tests I and II. Coagulants were applied at different concentrations (see Table 1), and analysis was performed before and after filtration to evaluate the effectiveness of two-stage clarification.

Table 1 – Parameters evaluated and fixed in Test III

	<b>Water pH</b>	<b>Rapid stirring time (min), speed 120 rpm</b>	<b>Coagulant concentration (mg L<sup>-1</sup>)</b>
Test III- Influence of coagulant concentration on the Water Clarification Process.	Fixed parameter: Pitaya pH 3 Pitaya natural pH Moringa natural pH Aluminum sulfate pH 6	Fixed parameter: Pitaya pH 3: 12 Pitaya natural pH: 12 Moringa natural pH: 1 Aluminum sulfate pH 6: 1	Variable evaluated: Pitaya: 25, 50, 75, 100, and 200 Moringa: 25, 50, 75, 100, and 150 Aluminum sulfate: 10, 15, 20, 25, and 30

Source: Author's 2026

### 2.1.5 Analysis of Potability Parameters

The potability parameters evaluated were:

a) Turbidity: measured before and after filtration to assess the removal of suspended particles,

b) Apparent Color and True Color ( $\lambda = 460 \text{ nm}$ ): analyses performed to verify the reduction of soluble colored compounds, with true color including filtration steps,

c) pH: monitored to observe variations induced by coagulants and check the need for adjustment to comply with legislation,

d) Dissolved Organic Carbon (DOC): assessed by the SUVA<sub>254</sub> method as an indicator of soluble organic matter after applying coagulants. UV absorption by organic matter can vary at pH <4 or >10 and is then standardized by adjusting the pH to 7 after the tests and before analytical measurements.

### 2.1.6 Parameters Statistical Analysis

Given that Test III involves evaluating a gradient of different doses between the coagulants, a linear and quadratic variance analysis was performed to identify the equation that best describes the relationship between the parameters evaluated (turbidity removal before and after filtration, apparent color, true color, pH, and DOC) and the different concentrations tested. The representativeness of the values was expressed by the R-value of each equation, indicating the degree of association between the variables (x and y) assessed. The best dose of each coagulant was determined by the derivative of the equation, allowing the identification of global maximum and minimum points. Statistical analysis was performed using SISVAR software developed by the Department of Statistics of the Federal University of Lavras (UFLA).

## 3 RESULTS AND DISCUSSIONS

### 3.1 Characterization of the water of Itapeva Lagoon

Table 2 presents the initial average values of the physical-chemical parameters of the water from Itapeva Lagoon before the optimizations conducted in Test III. The initial turbidity of the water (16.76 uT) exceeds the Maximum Permitted Value (MPV) established by Ordinance GM/MS 888/21 of 5 uT, which highlights the need for more

robust clarification to meet potability standards Brasil (2021). The average pH of 7.34 is within the permitted range (6-9), which favors the efficiency of natural coagulants, as indicated in studies on the use of cladodes as a sustainable alternative to chemical coagulants Idris et al. (2013).

Table 2 – Initial physical-chemical parameters of the Itapeva Lagoon water before the optimizations of Test III

Test	Turbidity (uT)	pH	Apparent color (uH)	True color (uH)	Dissolved Organic Carbon (mg L <sup>-1</sup> )
III- Influence of coagulant concentration on the Water Clarification Process	16.76	7.34	122.48	100.00	75.47
MPV <sup>a</sup>	5	6-9	15	NC <sup>b</sup>	NC

<sup>a</sup>MPV: Maximum Permitted Value, Ordinance GM/MS 888/21; <sup>b</sup>NC – Not covered in the potability ordinance

The apparent color and true color, with values of 122.48 uH and 100.00 uH respectively, indicate the presence of suspended particles and dissolved substances that contribute to the color of the water. Although Ordinance GM/MS 888/21 does not establish limits for these parameters, the effective removal of these compounds is essential for consumers to accept the water and for improving the efficiency of subsequent treatment processes. Studies with cladodes, such as those by Rayudu et al. (2022), highlight the efficiency of these materials in reducing turbidity and dissolved organic compounds, making them a promising solution for rural communities.

DOC measured at 75.47 mg/L indicates a high organic load, with the potential for the formation of disinfection byproducts, such as trihalomethanes (THMs), if not adequately reduced. Although Brazilian legislation does not specify a limit for DOC, studies such as that by Shafad et al. (2013) show that natural coagulants derived from

plants can offer effective alternatives for reducing these compounds while minimizing the environmental risks associated with the use of chemical coagulants.

### 3.2 Characterization of Coagulants

Identifying the chemical elements in coagulants is highly relevant to understanding their coagulation and flocculation capacity. Thus, the characterization of the coagulant powder used in the tests was conducted using the XRF technique. Table 3 presents the results for moringa powders, pitaya cladode, and commercial aluminum sulfate, highlighting that the values do not consider the humidity of the samples.

Table 3 – Oxide composition of powdered coagulants (moringa, pitaya, and aluminum sulfate) determined by XRF

Oxides	Aluminum Sulphate (%)	Moringa (%)	Pitaya (%)
SO <sub>3</sub>	78.25	49.93	3.45
K <sub>2</sub> O	-	23.61	38.00
Al <sub>2</sub> O <sub>3</sub>	18.26	-	-
P <sub>2</sub> O <sub>5</sub>	3.34	13.34	1.46
CaO	0.09	9.84	55.68
Fe <sub>2</sub> O <sub>3</sub>	0.04	0.68	0.71
ZnO	-	0.44	0.22
SiO <sub>2</sub>	-	1.63	-
MnO	-	0.12	0.12
CuO	0.02	0.28	0.20
Br	-	-	0.05
SrO	-	-	0.15
Rb <sub>2</sub> O	-	0.06	-
SeO <sub>2</sub>	-	0.08	-
Total	100.00	100.00	100.00

Obs.: Values expressed on a wet basis

For aluminum sulfate, the predominance of aluminum oxides (Al<sub>2</sub>O<sub>3</sub>) and sulfur (SO<sub>3</sub>), the main constituents of the reagent (Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>), is observed. The elements calcium (Ca), iron (Fe), and copper (Cu) identified probably derive from impurities in the commercial reagent.

As for moringa, the predominant oxides are distributed in three concentration ranges: the first group, with concentrations between 10% and 50%, includes sulfur (S), potassium (K), calcium (Ca), and phosphorus (P); the second, between 0.4% and 1.6%, includes silicon (Si), zinc (Zn), and iron (Fe); and the third, below 0.4%, includes manganese (Mn), copper (Cu), rubidium (Rb), and selenium (Se). Yin (2010) suggests that moringa seeds contain a significant diversity of coagulating agents that have not yet been identified, with cationic protein being the principal agent responsible for the coagulating capacity, although other compounds may contribute, albeit to a lesser extent.

The pitaya cladode powder is composed mainly of calcium (CaO), potassium (K<sub>2</sub>O), and sulfur (SO<sub>3</sub>) oxides, with concentrations of 55.68%, 38.00%, and 3.45%, respectively. Studies by Dick (2018) and Méndez et al. (2015) with cacti such as *Opuntia monacantha* and *Opuntia ficus-indica* also showed high levels of calcium and potassium, corroborating the results obtained for the cladode of pitaya (*Selenicereus undatus*), a cactus.

Both vegetable coagulants have major elements. Moringa coagulant has sulfur (50%), potassium (23%), phosphorus (13%), and calcium (10%) as predominant, while pitaya cladode stands out for its calcium (55%), potassium (38%), and sulfur (3%) contents.

Pitaya, the focus of this study, has seen a significant increase in cultivation in the extreme south of Santa Catarina and the northern coast of Rio Grande do Sul and generated large volumes of waste after harvest, as the cladode still has little practical application. Therefore, it was selected for additional analyses, including the determination of protein content, as described in the following item.

### **3.3 Protein Content of Pitaya Cladode**

The action of the coagulant derived from the pitaya cladode is still little explored, with the *Opuntia* genus being the most studied in the Cactaceae family for coagulation

purposes. In the case of moringa, the coagulation capacity is mainly attributed to the presence of proteins, emphasizing the protein fractions albumin and globulin present in the seeds Baptista et al. (2017).

Protein quantification of the pitaya cladode showed a mean value of 9.24% protein in the analyzed samples. This result is similar to that of Ortiz et al. (2013), who reported 7.39% protein for *O. ficus-indica* using the same method. Although this value is considered low for proteins, it suggests that they are not solely responsible for this species' coagulant power.

Studies indicate that other factors may contribute to the clotting ability of cacti. The Cactaceae family is known for producing mucilage, a complex carbohydrate with a high-water absorption capacity (Saenz et al. 2004). The galacturonic acid present in mucilage is indicated as one of the main components responsible for coagulation in *Opuntia* sp. However, Miller et al. (2008) observed that this substance contributes to only 50% of turbidity removal, indicating that other substances also play a relevant role in coagulation.

Furthermore, studies report the presence of antioxidant activity in the pitaya cladode of the species *H. undatus*, with emphasis on hydroxyl groups, which may be associated with its coagulation and flocculation capacity Som et al. (2021); Som et al. (2019).

### **3.4 Test III – Influence of coagulant concentration on the Water Clarification**

#### **Process**

Figure 1 presents the turbidity removal results, highlighting differences in the performance of the coagulants assessed. It is observed that vegetable coagulants (moringa and pitaya at natural pH) are more dependent on filtration to achieve significant removals, while aluminum sulfate and pitaya at pH 3 maintain high efficiency, even without the filtration step. This behavior is also demonstrated in Table 4, where the global maximum turbidity removal points are close for aluminum sulfate and pitaya

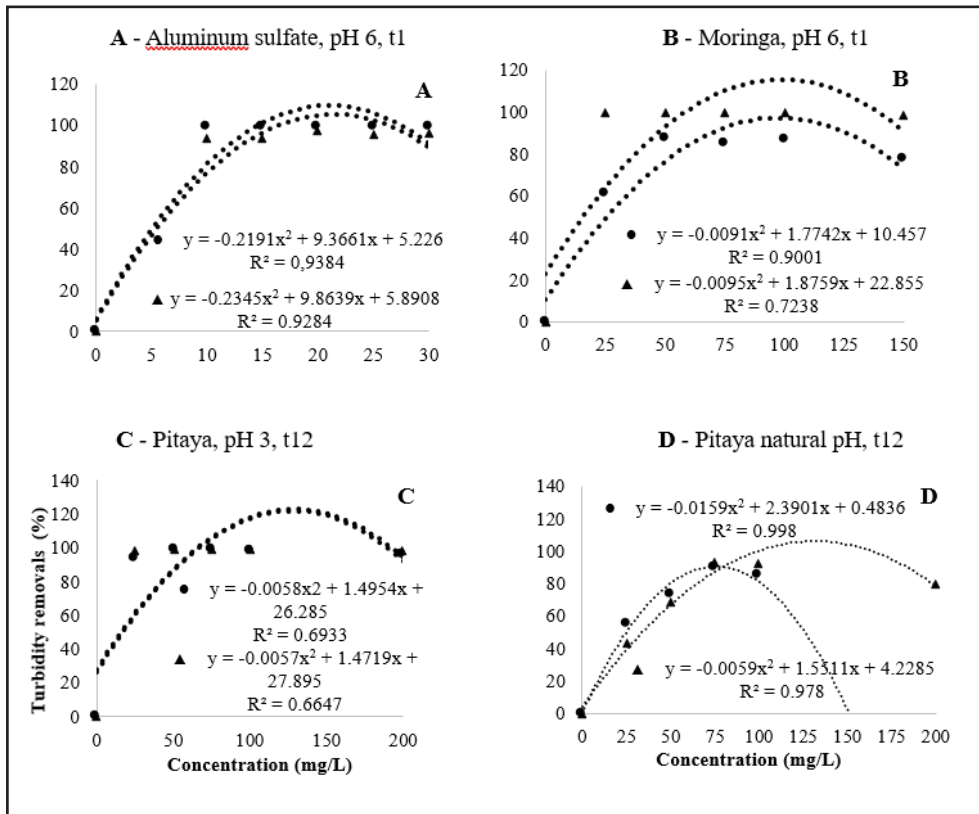
at pH 3 but differ in terms of the ideal concentration for moringa and pitaya at natural pH, indicating possible limited removal of suspended particles, or even addition of organic compounds to the medium.

Aluminum sulfate demonstrated removals higher than 90% in all concentrations assessed, with turbidity values below 1.19 uT, well below the 5 uT limit established by Ordinance GM/MS 888/21. The optimal concentration was ~21.37 mg/L (Table 4). This efficiency can be attributed to the coagulant's high solubility and its ability to remove particles such as clay, silt, and finely divided organic matter Parron & Muniz (2011). The small difference between the curves with and without filtration reinforces its effectiveness in direct clarification.

For moringa, the ideal concentration was 93.37 mg/L (Table 4), resulting in turbidity values below 2.6 uT without filtration and 0.14 uT with filtration. These results corroborate the findings of Hendrawati et al. (2016), who reported similar efficiency for concentrations close to 100 mg/L in wastewater. Although less efficient before filtration, moringa demonstrated high clarification potential after the filtration stage.

Pitaya at pH 3 showed comparable performance to aluminum sulfate, achieving turbidity removals above 90% at all concentrations assessed. The global peak was 128.91 mg/L without filtration and 129.11 mg/L with filtration. These results highlight the viability of the coagulant in acidic conditions where pH adjustment can occur naturally, such as in industrial effluents. On the other hand, pitaya at natural pH showed inferior performance at concentrations above 75.16 mg/L, even increasing turbidity at higher doses (150 mg/L), possibly due to the release of soluble organic matter, an issue that Figure 4 will discuss in more detail.

Figure 1 – Percentage of turbidity removal without filtration (●) and with filtration (▲) as a function of coagulant concentration (mg L<sup>-1</sup>): (A) Aluminum sulfate (pH 6, t1); (B) Moringa (natural pH, t1); (C) Pitaya (pH 3, t12); (D) Pitaya (natural pH, t12)



Source: Author's 2026

Table 4 – Global maximum and minimum points of the curves obtained for the coagulants according to the doses assessed: aluminum sulfate (pH 6), moringa (natural pH), and pitaya (pH 3 and natural pH)

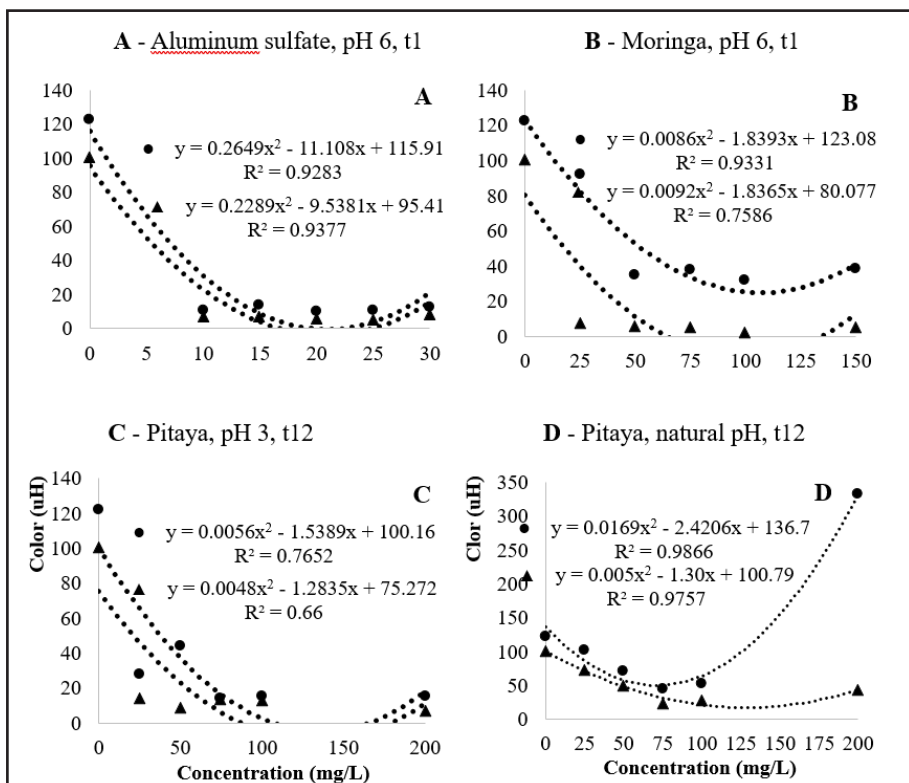
	Aluminum sulfate (pH 6)	Moringa (natural pH)	Pitaya (pH 3)	Pitaya (natural pH)
<b>Global maximum and minimum point (mg/L)</b>				
Turbidity Removal	21.37	93.37	128.91	75.16
Turbidity Removal After Filtration	21.03	98.73	129.11	131.44
Apparent Color	20.96	106.93	137.40	71.61
True Color	20.83	99.80	133.69	127.45
DOC	19.32	105.00	90.66	63.00

Source: Author's 2026

The filtration stage was essential to optimize the results of pitaya and moringa at natural pH, allowing turbidity removals of over 98%. This behavior highlights the importance of integrating filtration systems to maximize the efficiency of natural coagulants, especially under natural pH conditions.

Figure 2 presents the results for the apparent color and true color parameters, highlighting differences in performance between the coagulants assessed. Aluminum sulfate stood out by presenting apparent and true color values consistently below 14 uH in all concentrations, meeting the legal limits established by Ordinance GM/MS 888/21. The global minimum point was identified at 20.96 mg/L for apparent color and 20.83 mg/L for true color (Table 4), indicating almost total removal. This efficiency reflects the high solubility of the coagulant and its ability to form robust flocs that remove colored compounds in both the dissolved and particulate fractions.

Figure 2 – Apparent color (●) and true color (▲) parameters as a function of coagulant concentration (mg L<sup>-1</sup>): (A) Aluminum sulfate (pH 6, t1); (B) Moringa (natural pH, t1); (C) Pitaya (pH 3, t12); (D) Pitaya (natural pH, t12)



Source: Author's 2026

Moringa showed inferior performance for apparent color, with values above the normative limit in all concentrations assessed. The lowest value recorded was 32.11 uH, indicating limitations in using the vegetable coagulant in systems where the removal of apparent color is a priority. However, after filtration, the true color was reduced to levels compatible with legal standards, reaching a minimum value of 2.11 uH in 100 mg/L. These results corroborate the findings of Cardoso et al. (2008), who highlighted the importance of the filtration stage in reaching the normative limits in the use of moringa as a coagulant.

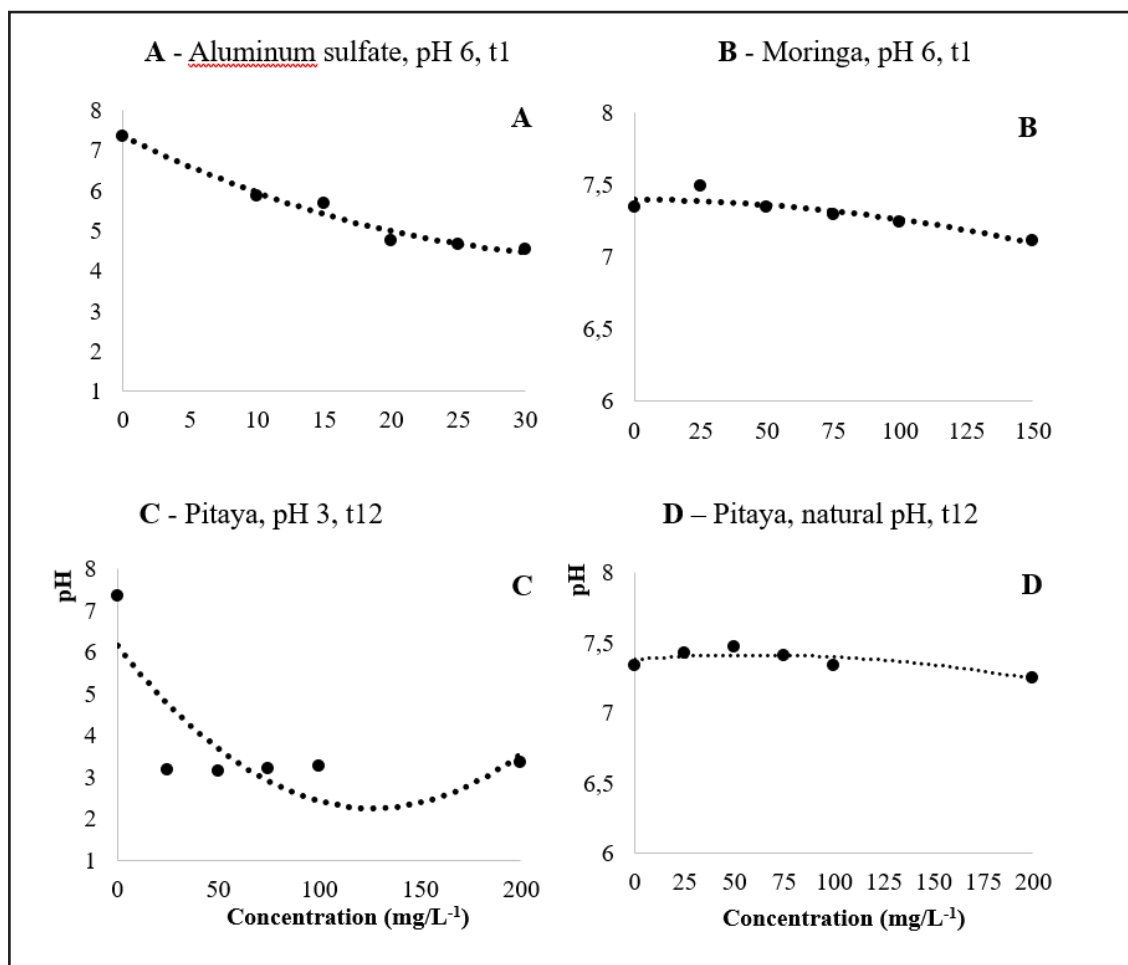
Pitaya at pH 3 demonstrated promising potential, with removals close to the 15 uH limit for apparent color at concentrations of 75 to 200 mg/L. The global minimum point was calculated at 137.40 mg/L for apparent color, suggesting the feasibility of total removal under controlled conditions. This performance reinforces the suitability of pitaya in treatment systems where pH adjustment for acidic conditions is technically feasible. However, pitaya presented significant limitations at natural pH, with the lowest apparent color value recorded at 44 uH, above the normative limit. Furthermore, doses higher than 75 mg/L increased color, possibly due to the release of soluble compounds from the coagulant itself, as will be discussed later about DOC.

The results indicate that filtration is a crucial step to improve the performance of plant coagulants, especially at natural pH. This integration is essential to maximize color and turbidity removal efficiency, making natural coagulants viable options for decentralized systems and specific water treatment contexts.

Figure 3 shows the evaluation of the final pH of the water after treatment with different coagulants, highlighting different behaviors between them. Aluminum sulfate demonstrated a marked reduction in pH, reaching 4.51 at the concentration of 30 mg/L. This significant acidification reinforces the need for pH adjustments before distribution to meet the limits established by Brazilian legislation (pH between 6 and 9) Brasil (2021). The dissociation of aluminum sulfate in water releases H<sup>+</sup> ions, reducing alkalinity by 0.50 mg/L and generating 0.44 mg/L of CO<sub>2</sub> per mg/L of coagulant added

Araújo (2021) Viessman & Hammer (2004), which represents a technical and economic limitation for its use in WTPs, due to the necessary pH adjustments.

Figure 3 – Final pH of water as a function of coagulant concentration ( $\text{mg L}^{-1}$ ): (A) Aluminum sulfate (pH 6, t1); (B) Moringa (natural pH, t1); (C) Pitaya (pH 3, t12); (D) Pitaya (natural pH, t12)



Source: Author's 2026

In contrast, moringa maintained a stable pH throughout the concentrations assessed (7.4 to 7.1), even at the maximum dose of 150  $\text{mg/L}$ . This behavior is corroborated by Michelan et al. (2021), who observed stability in the pH of treated water from the Poxin River in Aracaju, Sergipe, even at concentrations of up to 400  $\text{mg/L}$ . This characteristic makes moringa an interesting option for treatment systems aiming to minimize pH changes and the costs associated with correction.

The treatment with pitaya at pH 3 presented minimal variations (minimum pH point = 3.17; maximum pH point = 3.36), while at natural pH, the values ranged between 7.25 and 7.47. Despite the low variation in both conditions, pitaya at pH 3 would require pH adjustments before and after the process to comply with legislation, similar to aluminum sulfate. On the other hand, treatment with pitaya at natural pH would eliminate this need, although the overall performance for some drinkability parameters would be inferior, as discussed previously.

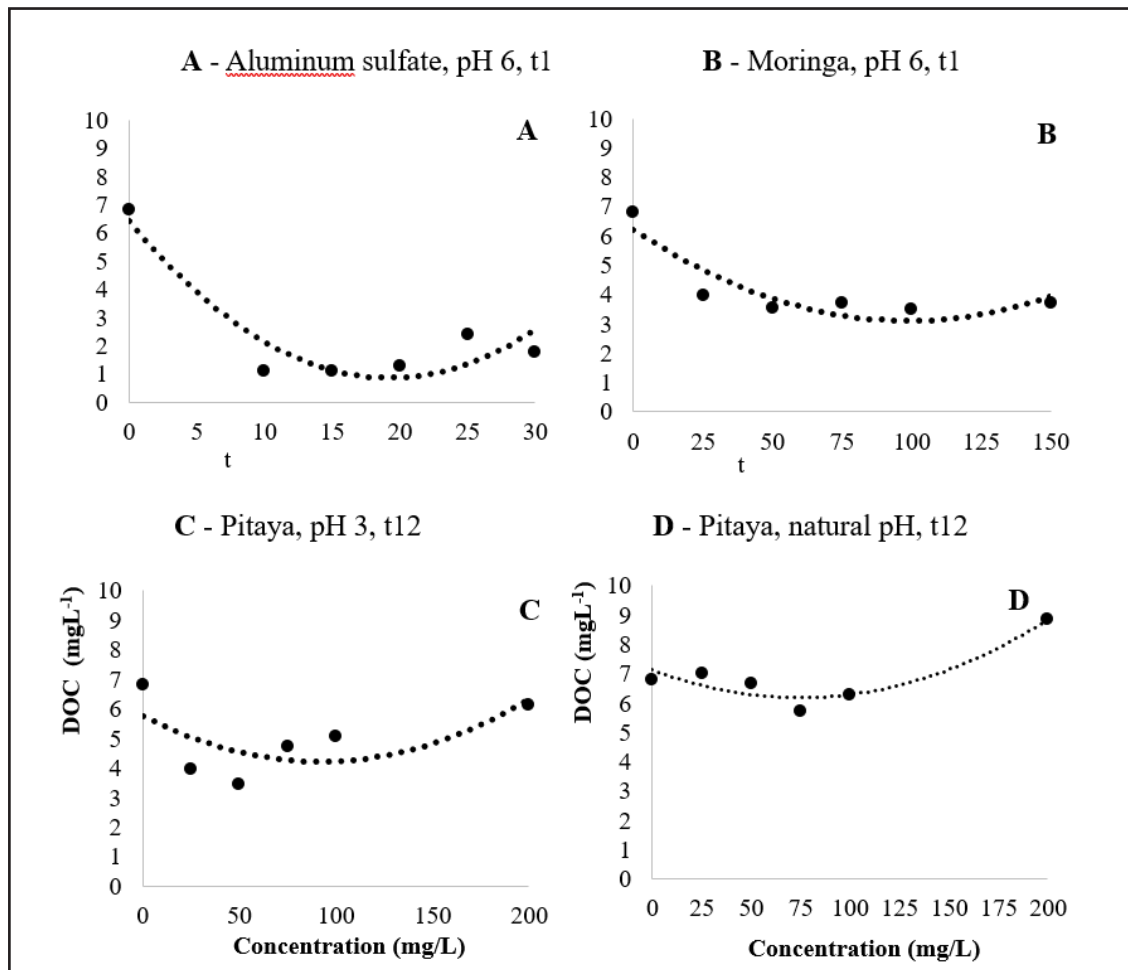
These results reinforce the operational advantages of plant coagulants, such as moringa and pitaya at natural pH, in contexts of lower complexity and operational cost. However, for large-scale applications or waters with specific characteristics, the use of pitaya at pH 3 may be technically viable as long as strategies for pH adjustment are economically justifiable.

Figure 4 shows the results of DOC as a function of coagulant concentration. Aluminum sulfate at pH 6 showed the highest DOC value at a concentration of 25 mg/L (2.42 mg/L) (Figure 4A), while raw water had an initial value of 6.8 mg/L. This behavior, characteristic of chemical coagulants that consume alkalinity, reinforces the need to correct the pH with lime or alkaline products and requires strict control of the aluminum residue in the treated water, which must be below 0.2 mg/L according to current legislation. Such technical and regulatory requirements limit aluminum sulfate's economic and environmental application in decentralized systems.

Moringa showed a consistent reduction in DOC, with values ranging from 3.51 mg/L to 3.99 mg/L (Figure 4B), representing almost 50% reduction in relation to raw water. The ideal concentration was identified as 105 mg/L, highlighting its effectiveness in waters with higher organic load, as also reported by Hendrawati et al. (2016). Unlike the studies by Baptista et al. (2017), who did not observe an increase in the soluble organic fraction with increasing doses, which demonstrates the stability of the vegetable coagulant in this parameter.

Pitaya at pH 3 achieved the highest DOC reduction at a concentration of 50 mg/L (Figure 4C), reaching 3.45 mg/L, approximately half the initial value of raw water. However, at higher concentrations (200 mg/L), the DOC returned to the initial level (6.8 mg/L), suggesting that moderate doses are more efficient for this parameter. These results reinforce the potential of pitaya at acidic pH, especially in controlled systems or with similar characteristics.

Figure 4 – Dissolved Organic Carbon as a function of coagulant concentration ( $\text{mg L}^{-1}$ ): (A) Aluminum sulfate (pH 6, t1); (B) Moringa (natural pH, t1); (C) Pitaya (pH 3, t12); (D) Pitaya (natural pH, t12)



Source: Author's 2026

At natural pH (Figure 4D), pitaya presented DOC values ranging from 5.71 mg/L (75 mg/L) to 8.87 mg/L (200 mg/L), evidencing an increase in dissolved organic matter at high doses. The ideal dose was identified at 63 mg/L, with a significant reduction in DOC compared to higher concentrations but still above the initial value of raw water. These results suggest that, at natural pH, adjustments in the coagulant preparation or application step could improve its efficiency, making pitaya more competitive for this parameter in real systems.

In the overall context, the DOC results reinforce the balanced performance of moringa and pitaya at pH 3 while highlighting the limitations of pitaya at natural pH for this parameter. Improvements in processing or operational design are promising ways to expand the practical applicability of this natural coagulant.

Table 5 summarizes the best results obtained for the parameters evaluated (turbidity, apparent color, true color, and DOC) with the three coagulants. Pitaya at pH 3 demonstrated excellent performance, meeting legal standards for turbidity and apparent color, with removals higher than 90% and values below normative limits. This performance is comparable to aluminum sulfate, with the advantage of being a natural and biodegradable coagulant, which makes it a promising alternative.

Table 5 – Best values obtained for turbidity, apparent color, true color, and DOC, compared to the limits established by Ordinance GM/MS n° 888/21 for turbidity and apparent color (MPV - Maximum Permitted Value)

Parameters evaluated	Aluminum sulfate (pH 6)	Moringa (natural pH)	Pitaya (pH 3)	Pitaya (natural pH)	MPV <sup>a</sup>
Best condition obtained					
Turbidity (uT)	0.59	2.04	0.09	1.75	5 uT
Turbidity after filtration (uT)	0.09	0.07	0.07	0.81	-
Apparent color (uH)	10.25	32.11	14.33	44.33	15 uH
True color (uH)	5.44	2.11	8.78	23.59	-
DOC (mg/L)	1.1	3.51	3.45	5.71	-

Source: Author's 2026

At natural pH, pitaya presented limitations for removing apparent color but obtained significant removals of turbidity, with values compatible with the normative limits in specific concentrations (50 - 100 mg/L). After filtration, the results demonstrated high efficiency for both turbidity and true color, highlighting the importance of filtration as a fundamental step to maximize the removal of colored particles and compounds. These findings reinforce the potential of pitaya in practical systems, where the integration of filtration allows for aligning efficiency and sustainability.

The results also highlight the versatility of pitaya as a natural coagulant, with the possibility of application in different operating conditions, as long as specific adjustments, such as pH control, are considered for technical and economic viability.

## **4 CONCLUSIONS**

This study demonstrated the potential of pitaya cladode as a natural coagulant in water treatment, highlighting its efficiency under specific conditions. At pH 3, pitaya showed performance comparable to aluminum sulfate, meeting the normative standards for turbidity and apparent color, with removals higher than 90%. However, the need for pH adjustments represents a technical and economic challenge for its application on an industrial scale. On the other hand, although color removal efficiency was limited, pitaya presented satisfactory results at natural pH for turbidity after filtration, indicating its viability in less restrictive treatment systems.

Plant-based coagulants, such as pitaya and moringa, offer a sustainable and environmentally friendly alternative, reducing dependence on chemical coagulants and associated impacts such as the generation of metal-containing waste. This study contributes to the valorization of agricultural waste, promoting innovative solutions aligned with the Sustainable Development Goals (SDGs), especially the goal of guaranteeing universal drinking water and sanitation.

Future recommendations include optimizing the performance of pitaya at natural pH, exploring modifications in coagulant preparation or combinations with

other materials; evaluating the efficiency of the coagulant in different types of water, especially in waters with lower organic load, to expand its applicability; investigating strategies that economically enable pH adjustment in large-scale systems; expanding the analysis to include additional potability parameters, such as removal of metals and insoluble organic matter, to meet more stringent regulations.

These perspectives strengthen the relevance of research and open paths for the development of accessible and sustainable technologies, especially aimed at rural communities and decentralized water treatment systems.

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