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Evaluation of microplastic removal efficiency through coagulation-flocculation process

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Microplastic (MP) contamination in water bodies represents a significant environmental challenge in Bolivia due to the limited efficiency of conventional wastewater treatment plants. This study evaluated MP removal through coagulation-flocculation using metallic salts (ferric and aluminum-based) and a natural bio-flocculant (*Opuntia ficus-indica*). Initially, jar tests were conducted to compare the removal efficiency of each flocculant under standardized conditions. Subsequently, the influence of pH, conductivity, and turbidity on MP removal was analyzed. The results demonstrated removal efficiencies ranging from 67.9% with the bio-flocculant to 86.68% with ferric sulfate. Notably, the combined use of inorganic salts and the bio-flocculant increased removal efficiency to 93.1%. Statistical analysis identified turbidity as the most influential parameter, limiting efficiency by 13.43% due to particle competition. These findings confirm that the interaction of physicochemical parameters is decisive for floc stability. This study proposes the use of bio-flocculants as a technically and environmentally viable alternative, adaptable to the Bolivian context, to optimize microplastic elimination in wastewater treatment systems.

Keywords: Microplastics; coagulation-flocculation; physicochemical parameters; bio-flocculant; *Opuntia ficus-indica*; removal

Evaluación de la eficiencia de remoción de microplásticos mediante el proceso de coagulación-floculación

La contaminación de los cuerpos de agua por microplásticos (MP) en Bolivia es un problema ambiental debido a la limitada eficiencia de las plantas de tratamiento convencionales. Este estudio evaluó la remoción de MP mediante coagulación-floculación, utilizando sales metálicas (féricas y aluminicas) y un bio-floculante natural (*Opuntia ficus-indica*). Inicialmente, a través de pruebas de jarras, se comparó la eficiencia de remoción utilizando cada floculante en condiciones similares. Después, se analizó cómo el pH, la conductividad y la turbidez afectan la remoción de MP. Los resultados mostraron eficiencias de remoción desde un 67,9% con el bio-floculante hasta un 86,68% con sulfato férrico. El uso combinado de sales inorgánicas con el bio-floculante incrementó la remoción hasta un 93,1%. El análisis estadístico identificó a la turbidez como el parámetro más influyente en la remoción de MP, limitando la eficiencia a un 13,43%. Los resultados comprueban que la interacción de los parámetros fisicoquímicos es determinante para la estabilidad de los floculos. El estudio propone el uso del bio-floculante como una alternativa técnica y ambientalmente viable, adaptable al contexto boliviano, para optimizar la eliminación de microplásticos en sistemas de tratamiento de aguas residuales.

Palabras clave: Microplásticos; coagulación-floculación; parámetros fisicoquímicos; bio-floculante; *Opuntia ficus-indica*; remoción

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1. Introduction

According to a report by the World Wildlife Fund (WWF), Latin America is the world's fourth-largest producer of plastic waste. In many South American countries, infrastructure for waste collection, recycling, and management is inadequate. This leads to an accumulation of plastic waste in landfills and the environment. Indeed, rapid urban growth often outpaces the capacity of waste management systems. International trade and tourism also contribute to the increase in plastic waste. Furthermore, policies and regulations to reduce plastic use and promote recycling are often insufficient, which contributes to the problem of microplastics (MP).

MP are particles smaller than 1 mm (Bermúdez and Swarzenski, 2021) that are classified as primary or secondary according to their origin. Primary MP are those intentionally produced with reduced dimensions (Rajala et al., 2020), while secondary MP result from the fragmentation of larger plastics (Lehtiniemi et al., 2018). This fragmentation process results from various physical, chemical, and biological processes (Tang et al., 2022), such as photo-oxidative, thermal, ozone-induced, mechanochemical, catalytic, and biodegradation (Singh and Sharma, 2008).

In Cochabamba, Bolivia, the presence of MP has been identified in various environments, including air, soil, and water bodies (Antezana, 2022; Linera, 2021; Oporto et al., 2021). The entry of these pollutants into aquatic ecosystems is attributed to both the decomposition of pre-existing plastic materials and the inadequate management of wastewater, industrial discharges, and surface runoff (Xue et al., 2021).

Due to their physical and chemical properties, MP exhibit persistence in the environment and have a high capacity to adsorb other organic and inorganic pollutants, contributing to their accumulation and transport in aquatic ecosystems (Guo and Wang, 2019; Jiang, 2018; Yao et al., 2022). Acting as vectors of pollutants, MP enter the food chain (Issac and Kandasubramanian, 2021), representing potential risks to both human health and aquatic species (Mamun et al., 2023).

The removal of MP from water bodies presents a challenge due to their wide distribution and continuous accumulation (Xiang et al., 2022). Among the available treatment alternatives, coagulation-flocculation (CF) has been identified as a viable method for the removal of MP due to its simplicity, relatively low costs, and energy efficiency (Khan et al., 2023; Tang et al., 2022). This physicochemical process destabilizes the surface charges of MP (Peydayesh et al., 2021), allowing them to agglomerate into larger and heavier flocs that can be separated from the water (He et al., 2023).

However, the removal efficiency using CF varies depending on the characteristics of the MP, such as particle size, surface charge, and polymer type. Smaller particles and materials with low surface affinity for the coagulants used are more difficult to remove (Sonal and Mishra, 2021). Furthermore, the physicochemical parameters of the water, such as pH, conductivity, and turbidity, influence particle stabilization mechanisms, affecting floc formation. Despite growing interest in this treatment method, there is a limited availability of studies evaluating the CF of MP in water bodies with minimal quality. Furthermore, the specific influence of the water's physicochemical parameters and intrinsic properties on the CF process is unknown, leading to uncertainty about removal efficiency.

Previous research on MP removal has shown that coagulation-flocculation processes can achieve varying removal efficiencies. For example, Rajala et al. (2020) achieved over 80% removal of MP from polyethylene in synthetic waters adjusted to neutral pH, while Frangenberg et al. (2024) observed that the presence of organic matter significantly reduced process efficiency.

2. Objectives

The main objective of this research was to evaluate the removal efficiency of MP through the CF process, analyzing the technical synergy between conventional metallic salts and a natural bioflocculant extracted from *Opuntia ficus-indica*. The study focused on identifying, through a robust experimental design and statistical analysis (ANOVA and Tukey test), the critical influence of physicochemical parameters such as pH, conductivity, and turbidity, with the aim of proposing a sustainable and scalable treatment alternative for the mitigation of emerging contaminants in water bodies of Global South countries.

3. Methodology

The methodology of this work is structured in three stages. First, the removal efficiency of low-density polyethylene (LDPE) and polyethylene terephthalate (PET) MP was determined using CF in a reference model system. Then, the effects of physicochemical factors of the medium on the CF performance of LDPE and PET MP were evaluated using inorganic salts as flocculants. Finally, the effectiveness of removing MP present in water by different flocculant materials was determined.

Initially, a study of the Rocha River was conducted to determine its microplastic concentration. This concentration will then be used to create a synthetic water sample for a jar test. The Rocha River is a Bolivian Amazonian river that flows through the department of Cochabamba. Originating in the Andes Mountains east of Sacaba, it passes through the city of Cochabamba and continues westward before turning southeast. It joins the Arque River, forming the Caine River. The Rocha River sampling point was located in the city of Cochabamba, upstream from the SEMAPA wastewater treatment plant and near the airport. The laboratory protocol for extracting MP from water samples followed a multi-stage process designed to eliminate organic interference and isolate plastic particles:

- Organic Matter Digestion: Initially, samples with high organic content were pre-treated with a potassium hydroxide (KOH 10%) solution in a 1:3 volume ratio and placed in an oven at 40°C for 24 hours. Subsequently, 30% hydrogen peroxide (H₂O₂) was added to the samples in a 1:1 ratio and incubated at 40°C for an additional 24 to 48 hours to complete digestion of the remaining organic material.
- Filtration and Washing: Once digestion was finalized, the treated samples were filtered through 0.45 µm pore diameter nitrocellulose filters and rinsed with 10 mL of distilled water.
- Density Separation: To separate the MP from denser inorganic residues, a zinc chloride (ZnCl₂) solution was utilized to reach a specific gravity of 1.37 g/mL (approximately 13.7 g of ZnCl₂ per 10 mL of sample).
- Final Collection: The supernatant, containing the isolated microplastics, was collected and vacuum-filtered again through a 0.45 µm nitrocellulose filter. These filters were then stored in covered Petri dishes within a desiccator to prevent atmospheric contamination or degradation before being weighed.

A concentration of 0.29 mg/L of MP particles was determined, so an approximate concentration of 0.3 mg/L of MP will be used in the CF experiments.

3.1. Removal efficiency of LDPE and PE as a reference model system

The MP material used as model contaminants in this research was LDPE and PET, acquired from the company Ravi (Cochabamba, Bolivia). The LDPE and PET pellets were mechanically crushed using a blender. Subsequently, the resulting fragments were sieved with stainless steel sieves, obtaining two size ranges: 180 - 300 µm, and 300 - 600 µm. This selection was based on the fact that these materials represent the most widely consumed polymers in Bolivia (Linera, 2021), while these particle sizes are characteristic of secondary MP generated through the fragmentation of plastic waste in surface water bodies (Rajala et al. 2020). Although the literature acknowledges the presence of particles smaller than 1 µm in treatment systems, the present study focuses on the micrometric fraction detectable through optical microscopy and conventional sedimentation methods, thereby establishing a baseline for the development of removal technologies adapted to the local context.

After sieving, the MP was added to a 2% HNO₃ solution, under continuous stirring for a period of 48 hours to eliminate possible traces of metals adsorbed on the surface of the MP (Fuentes, 2024). Subsequently, the MP were rinsed repeatedly with ultrapure water until a neutral pH was reached in the rinse water, indicating complete acid removal.

Finally, the MP were dried at room temperature and stored in light-protected glass jars. Laboratory-scale CF tests were performed using a programmable six-beaker jar test kit (FLOC-6; Spain) at room temperature (T≈25°C). Distilled water was used as a blank treatment to establish a reference system for evaluating CF efficiency.

Model suspensions were prepared with a MP concentration of 0.3 g/L, based on MP levels reported in the Rocha River. The initial physicochemical characteristics of the medium included a pH of 7.03, conductivity of 1.81 µS/cm, and a turbidity of 6.33 NTU.

To ensure homogenization of the medium, stirring was applied for 30 min at 175 rpm (Prokopova et al., 2021). Subsequently, a rapid mixing stage was performed for 5 min at 150 rpm, during which a dose of 20 mg/L of Fe₂(SO₄)₃ was added as a coagulant (Prokopova et al., 2021). This stage was followed by slow mixing for 15 min at 30 rpm and a 30 min sedimentation phase.

After the sedimentation period, a sample was taken from the water surface, taking care not to disturb the settled flocs. The samples were vacuum-filtered using 0.45 µm cellulose membrane filters to retain residual particulate matter. The filters were dried in an oven at 40°C for 30 min and then cooled in a desiccator for 20 min before weighing. The removal efficiency was calculated using Equation 1.

$$\text{Removal efficiency} = \frac{M_1 - M_2}{M_1} \quad (1)$$

Where:

- M₁: Initial mass of MP (0.3 g)
- M₂: Residual mass of MP after CF tests

3.2. Effects of physicochemical factors on CF performance

The identification of the physicochemical parameters of water influencing the CF process was carried out through a review of scientific literature. Google Scholar was used as the primary search tool, as it allows access to publications available in recognized scientific databases, such as ScienceDirect, SpringerLink, and Scopus, among others.

After analyzing these six parameters, pH, conductivity, and turbidity were selected for experimental testing, given that these parameters are comprehensive indicators of water quality and good indicators of the process. Furthermore, their selection was based on their relevance to the process and the feasibility of their control in the laboratory.

- pH: This parameter modifies the charge of the particles through the concentration of ions, affecting electrostatic interactions and floc formation (Peydayesh et al., 2021; Wang et al., 2005).
- Electrical conductivity (EC): This reflects the concentration of dissolved salts and ions in the medium. Both parameters are interdependent, as an increase in salts proportionally increases conductivity and, therefore, the ionic strength of the system. Its variation modifies the zeta potential of suspended particles, influencing electrochemical interactions and floc formation (Frangenberg et al., 2024).
- Turbidity: This represents the suspended solids content, and its concentration affects the interaction dynamics between suspended particles, including particulate matter and the coagulants/flocculants used (He et al., 2023). In this study, organic matter was indirectly incorporated into the turbidity tests, using vermicompost and kaolin as representations of the organic and inorganic fractions, respectively.

On the other hand, temperature was excluded as a study variable due to the difficulty of maintaining constant conditions during the tests performed with the jar test equipment.

The experimental design applied in this study was multifactorial, with three factors and two levels each (2^3), which allowed for a reliable evaluation of the effect of the water's physicochemical conditions on the removal efficiency of MP using CF. This approach made it possible to identify both the main effects of each factor and the possible interactions between them. The factors evaluated in the experiment were the following:

- MP material: Two types of MP, LDPE and PET, were analyzed, selected due to their high presence in water bodies.
- MP size: Two particle size ranges were established: 180–300 μm and 300–600 μm .
- Physicochemical conditions: For each of the selected physicochemical parameters, two value levels were defined that reflect the typical variations in water bodies of minimum quality (Table 1).

Table 1: Levels of physicochemical parameters

Parameter	Low level	High level
pH	6	9
EC [$\mu\text{S}/\text{cm}$]	500 to 1,600	> 1600
Turbidity [NTU]	50 to 100	> 200

Although the experimental design was multifactorial, the statistical analysis was structured as a single-factor analysis based on the combination of variables evaluated at each stage of the study. This allowed for the individual assessment of the effect of each physicochemical parameter of the medium on removal efficiency. This approach enabled a more precise and controlled analysis of each factor, without interference from other elements of the system.

In addition to the described factorial design, an additional treatment with distilled water, without modifications to the physicochemical parameters, was included as a reference or blank system. Although this treatment is not part of the multifactorial design (2^3), it was incorporated into the statistical analyses (ANOVA) to compare the removal efficiency obtained under unmodified conditions with that obtained under simulated minimum quality water conditions.

The three physicochemical parameters of the medium (pH, EC, and turbidity) were modified as follows:

- pH was adjusted to values of 6 and 9, representing low and high levels, respectively, by adding 0.5 M solution of NaOH and HCl.
- EC was modified by adding a 1 M NaCl solution until low (500–1600 $\mu\text{S/cm}$) and high (>1600 $\mu\text{S/cm}$) levels were reached.
- Turbidity: Two levels of this parameter were established: low (50–100 NTU) and high (>200 NTU), using kaolin and vermicompost as representative materials of inorganic and organic particles, respectively. The kaolin stock solution was prepared by dissolving 20 g of kaolin in 1,000 mL of ultrapure water, stirring at 800 rpm for 10 min, and then allowing it to stand overnight at room temperature. The vermicompost stock solution was prepared by dissolving 1 g of vermicompost in 50 mL of 0.1 M NaOH, stirring at 800 rpm for 6 hours (He et al., 2023). For the high turbidity level, 26 mL of the kaolin stock solution and 20 mL of the vermicompost stock solution were added. For the low turbidity level, 9.1 mL and 7 mL were used, respectively, in both cases diluting to a final volume of 1,000 mL with ultrapure water.

The CF test was performed as described for the reference model system.

In the pH and conductivity tests, once the sedimentation time had elapsed, a sample of the supernatant was extracted, taking care not to disturb the settled flocs. The samples were vacuum filtered using 0.45 μm cellulose membrane filters. The filters were then dried in an oven at 40 °C for 30 min, cooled in a desiccator for 20 min, and weighed.

In the turbidity variation tests, an oxidative digestion treatment was performed to remove organic matter, adapting the protocol of Linera (2021). For this purpose, 30% hydrogen peroxide (H_2O_2) was added in a 1:1 ratio to the supernatant sample. The samples were kept covered with aluminum foil and placed in an oven at 40 °C for 24 hours, or until the organic matter was no longer visible. Subsequently, a density separation was performed using a zinc chloride (ZnCl_2) solution in a proportion such that the final concentration of the solution with the sample was 1.37 g/mL. Finally, the supernatant was vacuum filtered, dried and weighed to calculate the MP removal efficiency using equation 1.

To evaluate the effect of the medium's physicochemical parameters on the removal efficiency of MP, a one-way analysis of variance (ANOVA) was used. This analysis allowed for the individual evaluation of the effect of each physicochemical parameter (pH, conductivity, and turbidity) on MP removal efficiency using CF, while keeping the MP material and particle size range constant in each case.

The experimental data were processed using Minitab software, widely used in studies due to its ability to perform analysis of variance and generate reliable results. All analyses were performed with a 95% confidence level ($\alpha = 0.05$). For each one-way analysis, the following statistical hypotheses were formulated:

- Null hypothesis (H_0): There are no significant differences in PM removal efficiency between the levels of each physicochemical parameter evaluated.
- Alternative hypothesis (H_1): At least one of the levels of the evaluated physicochemical parameter shows a significant difference in PM removal efficiency.

When the p-value obtained was less than 0.05, the null hypothesis was rejected, indicating that the analyzed physicochemical parameter had a significant effect on removal efficiency. In these cases, a Tukey test was applied to identify which levels differed significantly from each other.

3.3. MP removal effectiveness of flocculants

Two inorganic flocculants were tested for treating the MP-polluted water:

- Ferric chloride (FeCl_3)
- Aluminum sulfate ($\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$).

The initial aim was to determine the best coagulant between ferric chloride (FeCl_3) and aluminum sulfate ($\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$) over a wide range of concentrations (Table 2).

Table 2: Concentration range of tested inorganic flocculants

Flocculant	C (mmol/L)	C (mg/L)
Al^{3+}	0.300	8.090
	0.450	12.140
	0.600	16.190
	0.750	20.240
	0.900	24.280
	1.050	28.330
Fe^{3+}	0.185	10.330
	0.370	20.660
	0.555	30.990
	0.740	41.330
	0.925	51.660
	1.110	61.990

The CF tests were performed with the conditions described for the reference model system. Then, the prickly pear mucilage, a bio-flocculant, was evaluated to remove MP by CF. The prickly pear cactus is a tree-like plant that can reach 3 to 5 meters in height. The cladodes, also called pads, are modified, flattened stems, 30 to 40 cm long, 15 to 25 cm wide, and 1.5 to 3 cm thick.

Research has shown that the mucilage of *Opuntia ficus-indica* possesses molecular and physicochemical characteristics suitable for use as a coagulant. Studies have highlighted the presence of a branched polymer with an average molecular weight (0.44 kDa), an oligosaccharide structure, hydroxyl and carboxyl functional groups, and an anionic nature, thus ensuring effectiveness in the coagulation-flocculation process for water treatment.

The prickly pear cactus contains mucilage, a complex polysaccharide composed primarily of galactose, arabinose, and xylose. This mucilage has a strong capacity to adsorb suspended particles in water, making them heavier and facilitating their settling. Furthermore, studies have shown that *Opuntia ficus-indica* mucilage can eliminate turbidity, suspended solids (SS), and chemical oxygen demand (COD) from water (Otálora et al., 2022; Betatache et al., 2014).

Regarding the experimental steps, six cladodes were used. After removing the spines from each cladode, they were thoroughly rinsed with distilled water. The cladodes were then weighed on a precision balance to determine their initial weight. Next, using a sharp knife, the outer layer of the cladodes, called the cuticle, was removed, leaving only the inner pulp. The resulting pulp was cut into small, even strips to maximize drying efficiency. These strips were placed in a dehydrator for 48 hours at approximately 60°C. After 48 hours, the dried strips were removed from the dehydrator and weighed again.

Following dehydration, the cladode pulp strips underwent a considerable reduction in size. They became fragile and brittle, which was taken advantage of by manually grinding them in a mortar. Once ground, the resulting powder underwent a sieving step to ensure a

homogeneous particle size distribution. The goal was to guarantee that the particles had a diameter of less than 0.5 mm, in order to optimize subsequent pigment extraction. To achieve this fineness, a series of standardized Tyler sieves was used. Thus, only the particles that successfully passed through the mesh of the sieves, size 8 (2.36 mm), 20 (850 µm), and 40 (425 µm), were retained; these are what we call the "fines." From the resulting "fines," the extraction process was applied to remove chlorophyll and other pigments, using 96% ethanol as a solvent, in a Soxhlet extractor for approximately 2.5 hours. The extracts were dried and the powder dissolved with distilled water. Different concentrations of mucilage were tested (Table 3).

Table 3: Concentration range of tested inorganic flocculants

Flocculant	C (mg/L)
Prickly pear mucilage	7.5
	15.0
	30.0
	60.0
	120.0
	180.0

The CF tests were performed with the conditions described for the reference model system. Once the most effective concentrations of each flocculant were determined, the test was carried out by mixing each inorganic flocculant with the organic coagulant to see the effect of this mixture on the removal efficiency of MP by CF.

4. Results

4.1. MP removal effectiveness

Distilled water treatment was used as the reference system for both MP size ranges. Under these conditions, removal efficiencies from 82.24% to 86.69% were obtained for the 180–300, depending on size ranges (Table 4).

Table 4: Levels of physicochemical parameters

Size range [µm]	PE MP removal	PET MP removal
180 – 300	86.68 ± 0.01%	86.69 ± 0.01
300-600	82.24 ± 2.31%	82.24 ± 2.32

4.2. MP removal in different CF conditions

Two pH values, electrical conductivity, and turbidity were tested to observe the effects of these parameters on the removal of MP by CF.

Table 5: Efficiency of MP removal under different pH conditions

Size range [μm]	PE		PET	
	pH		pH	
	6	9	6	9
180 – 300	$82.23 \pm 2.35\%$	$74.48 \pm 2.57\%$	81.13 ± 4.75	73.35 ± 7.85
300-600	$82.23 \pm 2.34\%$	$76.67 \pm 0.01\%$	73.39 ± 4.52	80.04 ± 7.19

When analyzing the effect of pH (Table 5), it was observed that in acidic or alkaline conditions, it negatively affects the efficiency of the CF\ process compared to the control. For MP of 180–300 μm , the efficiency decreased to values between 81.13% and 82.23% at pH 6, and to 74.48% at pH 9. Similarly, the 300–600 μm range showed efficiencies between 73.39% and 82.23% at pH 6, and between 74.48% and 76.67% at pH 9. In general, removal was slightly more efficient in acidic media, which is attributed to the predominance of positively charged ferric species that favor electrostatic attraction with the MP, a behavior that agrees with that described by Stumm and Morgan (1962) regarding ferric hydrolysis products in slightly acidic solutions. On the other hand, the decrease in efficiency at pH 9 could be associated with lower charge neutralization effectiveness, although it was observed that for the 300–600 μm range, the efficiency increased compared to the value at pH 6. This can be explained by the fact that a smaller size increases the available adsorption sites, favoring interaction with the coagulant and agglomeration of the MP (Dawood et al., 2024).

Table 6: Efficiency of MP removal under different EC conditions

Size range [μm]	PE		PET	
	EC [$\mu\text{S}\cdot\text{cm}^{-1}$]		EC [$\mu\text{S}\cdot\text{cm}^{-1}$]	
	500 – 1600	> 1600	500 – 1600	> 1600
180 – 300	$86.67 \pm 3.85\%$	$87.78 \pm 5.80\%$	84.47 ± 2.26	80.04 ± 0.03
300-600	$54.46 \pm 3.52\%$	$80.01 \pm 18.15\%$	80.02 ± 7.22	78.92 ± 4.87

The results indicate that EC negatively impacts the removal trend, with MP removal efficiency decreasing as ionic concentration increases relative to the experimental control (Table 6). For 180–300 μm particles, efficiency decreased from 86.69% in the blank to 80.04% at conductivities above 1600 $\mu\text{S}/\text{cm}$. In the 300–600 μm range, although an improvement was observed compared to low salinity levels (from 54.46% to 80.01% at the high level), the final value remained below that recorded with distilled water.

This behavior is associated with the dynamics of the electrical double layer. The increase in ionic strength reduces the zeta potential and electrostatic repulsion between particles, theoretically favoring floc formation. However, exceeding a critical ionic concentration level leads to excessive compression of the diffuse layer surrounding the MP. This excess of ions can cause a reversal of the surface charge or colloidal re-stabilization, preventing the

formation of stable aggregates and compromising the efficiency of the CF process (Bohinc et al., 2001).

Finally, the literature reports that in systems treated with electrolytes, ions generate an electrostatic shield that reduces repulsion due to the accumulation of counterions (Schneider et al., 2011). However, the secondary stabilization phase observed at high conductivities in this study confirms that the interaction of physicochemical parameters is crucial for floc stability and the effective removal of contaminants in wastewater treatment systems.

Table 7: Efficiency of MP removal under different turbidity conditions

Size range [μm]	PE		PET	
	Turbidity [NTU]		Turbidity [NTU]	
	50 – 100	> 200	50 – 100	> 200
180 – 300	31.26 $\pm$ 24.53%	13.43 $\pm$ 0.75%	60.05 $\pm$ 11.10	31.23 $\pm$ 12.26
300-600	40.14 $\pm$ 33.22%	42.28 $\pm$ 24.13%	51.17 $\pm$ 7.47	29.01 $\pm$ 13.32

Increasing the concentration of suspended particles progressively decreases the removal of MP (Table 7). For the 180–300 μm size range, efficiency dropped drastically from 86.69% in the experimental blank to a mere 13.43% under high turbidity conditions (>200 NTU). Similarly, in the 300–600 μm range, removal efficiency fell from the original 82.24% to 29.01% at the highest turbidity levels evaluated.

These results demonstrate that a high suspended solids load negatively interferes with the CF process, limiting the formation of stable flocs due to direct competition between MP and other particles present in the medium. This behavior is consistent with the findings reported by He et al. (2023), who showed that increased suspended particles hinder effective contact with the coagulant, affecting microplastic aggregation. Furthermore, the need to adjust coagulant dosages in highly turbid media has been noted by Li et al. (2016), given that solids significantly influence the stability and effectiveness of the colloidal system.

Finally, the greater variability observed in the results under high turbidity conditions is attributed to the heterogeneous nature of the medium, which generates an uneven distribution of particles and affects the reproducibility of the tests. Statistical analysis identified turbidity as the most influential parameter in PM removal, acting as a limiting factor for efficiency due to particle competition.

4.3. Effects of physicochemical factors on MP removal

To evaluate the impact of the medium's physicochemical parameters on microplastic removal efficiency, an ANOVA test was performed, followed by a Tukey post-hoc test to identify specific levels with statistically significant differences. This statistical approach allowed for the confirmation of significant variations ($p < 0.05$) across the different levels of pH, conductivity, and turbidity evaluated in the study.

Table 8: Analysis of variance for the effect of physicochemical parameters on the removal efficiency of MP

		PE		PET	
		Contribution	p-value	Contribution	p-value
pH	180–300 µm	93.94%	0	73.72%	0.018
	300–600 µm	80.88%	0.007	57.18%	0.078
EC	180–300 µm	3.21%	0.907	90.40%	0.001
	300–600 µm	76.62%	0.013	14.25%	0.63
Turbidity	180–300 µm	98.67%	0	97.50%	0
	300–600 µm	85.53%	0.003	98.48%	0

Statistical analysis using one-way ANOVA (Table 8) confirmed that the evaluated physicochemical parameters have a decisive and statistically significant influence (p-value < 0.05) on MP removal efficiency. Turbidity stood out as the most critical factor, explaining up to 98.67% of the total variability in certain size ranges, demonstrating that the presence of suspended particles directly competes with MP for the coagulant's active sites. pH explained between 73.72% and 93.94% of the variance, confirming that the acidity or alkalinity of the medium alters the charge neutralization capacity. Finally, conductivity also showed a considerable influence (up to 90.40%), where elevated levels can generate weaker flocs due to the formation of ionic complexes that limit particle aggregation.

Table 9: Groups of efficiency means according to the level of the physicochemical parameter using Tukey's test

		PE			PET		
		Control	Low level	High level	Control	Low level	High level
pH	180–300 µm	A	B	C	A	AB	B
	300–600 µm	A	A	B	A	A	A
EC	180–300 µm	A	A	A	A	A	B
	300–600 µm	A	A	B	A	A	A
Turbidity	180–300 µm	A	B	C	A	B	C
	300–600 µm	A	B	B	A	B	C

Tukey's multiple comparison tests revealed clustering patterns that identify the optimal and critical conditions for treatment (Table 9). In most experiments, the control treatment (neutral

pH and low turbidity/conductivity) was grouped with Group A, achieving the highest average efficiencies (approximately 86.68%). In contrast, high turbidity (>200 NTU) and alkaline pH (9) conditions were independently grouped at the lowest efficiency levels, confirming that deviations from neutrality and excess solids hinder the formation of stable flocs. These findings are consistent with those reported by Prokopova et al. (2021) and He et al. (2023), who indicate that in alkaline or highly turbid media, electrostatic repulsion and particle competition predominate, drastically reducing the effectiveness of the CF process.

4.4. Comparison of flocculant efficiency

Ferric chloride and aluminum sulfate were initially tested and compared to determine which was most effective for treating the microplastic-polluted water (Table 10).

Table 10: MP removal comparison

Parameter	MP removal (%)
Fe ³⁺	75
Al ³⁺	84.8
Mucilage	67.9
Fe ³⁺ -Mucilage	93.1
Al ³⁺ -Mucilage	74.2

Ther aluminum sulfate provides a higher rate of MP removal than ferric chloride. Thus, according to the results, the optimal dose for ferric chloride is 51.66 mg/L, with an MP removal rate of 75%, and for aluminum sulfate, the optimal dose is 20.24 mg/L, with an MP removal rate of 84.8%. Then, the optimal concentration was determined for the bio-flocculant. The concentration for *Opuntia ficus-indica* as a primary coagulant was identified as 120 mg/L (Table 10).

Experimental results demonstrated a direct correlation between the treatment dosage and both floc size and sedimentation velocity. Notably, the aggregates formed with the natural bio-flocculant were significantly larger than those produced by inorganic coagulants alone. In the subsequent phase, evaluating the bio-flocculant as a secondary aid, standardized doses of aluminum sulfate (20.24 mg/L) and ferric chloride (51.66 mg/L) were combined with the previously determined optimal bio-flocculant dose (120 mg/L).

The results shows that the ferric chloride and bio-flocculant synergy achieved a superior MP removal efficiency of 93.1%. It outperforms the 74.2% observed for the aluminum sulfate combination with the bio-flocculant. Furthermore, the ferric system exhibited enhanced floc size and accelerated settling rates compared to its aluminum-based counterpart.

Comparative analysis indicates that while ferric chloride's efficiency increased from 75% to 93.1% upon the addition of the bio-flocculant, aluminum sulfate's performance decreased from 84.8% to 74.2%. These findings confirm that the integration of the bio-flocculant provides a substantial technical advantage, specifically when paired with ferric chloride.

The technical superiority of the Fe³⁺-mucilage system (93.1% removal) over the exclusive use of inorganic salts was reflected not only in the removal efficiency, but also in the morphology of the aggregates formed. It was visually observed that the addition of the bioflocculant generated larger flocs with a significantly higher sedimentation velocity than that achieved using the inorganic coagulant alone.

This behavior suggests that the mucilage, as a highly branched high-molecular-weight polymer containing hydroxyl and carboxyl functional groups, operates through an adsorption bridging mechanism (Peydayesh et al., 2021). This polymeric network traps the MP destabilized by iron, forming denser flocs that are more resistant to shear forces, thereby enhancing process stability under variations in water quality (Tang et al., 2022).

5. Conclusions

This research focused on MP pollution as a pervasive environmental challenge in Bolivia, affecting aquatic ecosystems. The limited efficiency of conventional wastewater treatment plants and inadequate waste management facilitate the persistence and accumulation of these pollutants in aquatic ecosystems.

The CF process proved to be a technically viable method for MP removal, although its effectiveness is heavily dictated by the water's physicochemical parameters. Statistical analysis identified turbidity as the most critical limiting factor, explaining up to 98.67% of the removal variability due to direct competition between suspended solids and MP for coagulant active sites. Furthermore, deviations from neutral pH and excessive electrical conductivity were found to hinder floc stability through charge neutralization interference and double-layer compression.

The most significant finding of this study is the superior performance of the natural bio-flocculant derived from *Opuntia ficus-indica*. While aluminum sulfate initially showed higher efficiency than ferric chloride as a standalone coagulant (84.8% vs. 75%), the synergy between ferric chloride and the cactus mucilage achieved the highest overall MP removal rate of 93.1%. This combination not only improved removal rates but also produced larger aggregates and accelerated sedimentation velocities.

From a practical application perspective, the implementation of this process in existing treatment plants in Bolivia is highly feasible. *Opuntia ficus-indica* is an abundant species in regions such as Cochabamba, and its processing requires low-cost technology, thereby facilitating the scalability of the system in rural or resource-limited settings. Furthermore, the reduced use of aluminum salts decreases the associated health risks and generates sludge containing a biodegradable organic fraction, in alignment with the principles of circular economy and environmental sustainability. Future research should evaluate the effectiveness of the system in the nanoplastic range and assess operational costs for large-scale industrial integration.

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Use of Generative Artificial Intelligence

AI tools were used for language improvement

Communication aligned with the Sustainable Development Goals

