# Coagulant and flocculant effect of *Opuntia ficus-indica* in water treatment

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*Efecto coagulante y floculante de Opuntia ficus-indica en el tratamiento del agua*

*Efecte coagulant i floculant d'Opuntia ficus-indica en el tractament d'aigües*

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## ABSTRACT

One of the most relevant processes in potable and wastewater treatment plants is coagulation-flocculation, which gives rise to the destabilization of dissolving solids, for the subsequent generation of flocs using a coagulating agent. Aluminum sulfate ($Al_2(SO_4)_3$) is the most used coagulant internationally, due to its efficiency and low cost. However, its utilization can leave a residue of aluminum in water and bring with it a variety of health problems due to its bioaccumulative characteristics, implying both the deterioration of ecosystems and problems for human health. In this regard, it is necessary to establish alternatives that avoid the permanence of this heavy metal in water, so that the mucilage of *Opuntia ficus-indica* becomes a natural coagulant of great interest. Likewise, it is a sustainable alternative for water treatment, given its characteristics of biodegradability, low toxicity, commercial cost, relative abundance, renewability, and high efficiency, allowing a low generation of sludge, which can be biodegraded through a fair treatment with a high valuation spectrum.

**Keywords:** aluminum sulfate, coagulation-flocculation, mucilage, *Opuntia ficus-indica*, water resource

## RESUMEN

Uno de los procesos de gran relevancia en las plantas de tratamiento de aguas potables y residuales es la coagulación-floculación, donde se da la desestabilización de los sólidos disueltos, para la posterior generación de flóculos mediante el uso de un agente coagulante. El sulfato de aluminio ($Al_2(SO_4)_3$) es el coagulante más utilizado a nivel internacional, debido a su eficiencia y bajo costo. Sin embargo, su uso puede dejar un remanente de aluminio en el agua y traer consigo una variedad de problemas sanitarios debido a sus características bioacumulativas, implicando tanto el deterioro de los ecosistemas, como problemas para la salud del ser humano. En este sentido, se hace necesario establecer alternativas que eviten la permanencia de este metal pesado en el agua, de modo que el mucilago de *Opuntia ficus-indica* se convierte en un coagulante natural de gran interés. De igual manera, es una alternativa sostenible de tratamiento de las aguas, dadas sus características de biodegradabilidad, baja toxicidad, costo comercial, abundancia relativa, renovabilidad y alta eficiencia, permitiendo una baja generación de lodos, los cuales pueden ser biodegradados a través de un tratamiento asequible con un alto espectro de valorización.

**Palabras clave:** coagulación- floculación, mucilago, *Opuntia ficus-indica*, recurso hídrico, sulfato de aluminio.



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## RESUM

Un dels processos més rellevants a les depuradores d'aigües potables i residuals és la coagulació-floculació, que dóna lloc a la desestabilització de sòlids en dissolució, per a la posterior generació de flocs mitjançant l'ús d'un agent coagulant. El sulfat d'alumini ($Al_2(SO_4)_3$) és el coagulant més utilitzat a nivell internacional, per la seva eficiència i baix cost. No obstant això, el seu ús pot deixar una resta d'alumini a l'aigua i comportar una varietat de problemes de salut a causa de les seves característiques bioacumulables, que implica tant el deteriorament dels ecosistemes com problemes per a la salut humana. En aquest sentit, cal establir alternatives que evitin la permanència d'aquest metall pesat a l'aigua, de manera que el mucílag d'*Opuntia ficus-indica* esdevingui un coagulant natural de gran interès. Així mateix, és una alternativa sostenible per al tractament de l'aigua, donades les seves característiques de biodegradabilitat, baixa toxicitat, cost comercial, relativa abundància, renovabilitat i alta eficiència, permetent una baixa generació de fangs, que poden ser biodegradats mitjançant un tractament just i amb una alta valoració. espectre.

**Paraules clau:** coagulació-floculació, mucílag, *Opuntia ficus-indica*, recursos hídrics, sulfat d'alumini.

## INTRODUCTION

The treatment process for water potabilization generally encompasses several stages. Initially, it involves the removal of sands and similar solids, followed by the chemical oxidation of organic compounds present in the water. Subsequently, the processes of coagulation and flocculation take place, which are essential physicochemical treatments aimed at overcoming the repulsive forces between the finest colloidal sediments present in water. These processes involve the agglomeration and extraction of these sediments through the addition of inorganic or organic chemical substances [1]. The objective is to achieve the destabilization and agglomeration of colloidal particles, facilitating their subsequent separation in later stages of the treatment. Furthermore, adsorption is carried out, where soluble substances are captured by surface materials that act as filters [2]. Ultimately, the disinfection process is implemented, involving the addition of a disinfectant agent, typically chlorine, to effectively eliminate microorganisms such as *Escherichia coli* or *Legionella sp.* [3]. These microorganisms represent a significant pathogenic risk in water supplies. Through these potabilization processes, citizens are provided with water that complies with current regulatory standards. However, a challenge associated with the coagulation-flocculation process lies in the use of inorganic coagulants, which are permitted in the regulations of many countries worldwide. That is the case of one of the most used coagulant agent, the aluminum sulfate ($Al_2(SO_4)_3$), since it can be particularly hazardous to human health due to its bioaccumulative characteristics of aluminum (Al) [4]. In fact, previous research associates this compound with the development of degenerative diseases [5, 6]. Currently, several strategies have been implemented worldwide to replace $Al_2(SO_4)_3$ with the bark of the rain tree (*Pithecellobium saman*), species like *Malvaviscus arboreus*, *Heliocarpus popayanensis*, and *Hylocereus undatus* [7], potato peel [8], seeds of the golden shower tree (*Cassia fistula*) [9], leave extract of fique (*Furcraea sp.*) [10], and *Aloe vera* [1,11]. Nevertheless, it is necessary to generate additional strategies with the same effect in terms of efficiency regarding water treatment without the associated health risks of $Al_2(SO_4)_3$. In this regard, the use of nopal, also known as prickly pear or cactus (*Opuntia ficus-indica*), in the coagulation-flocculation process is proposed. Nopal is defined as a large cactus native to arid areas of South, Central, and North America [12] that is used as a natural coagulant and an alternative to replace $Al_2(SO_4)_3$ in water treatment systems due to its physicochemical properties, aiming to mitigate the collateral damages caused by this compound in the human body. Thus, nopal constitutes an eco-friendly technique that consumes fewer solvents, time, and energy compared to the use of $Al_2(SO_4)_3$ [13]. At the same time, nopal is recognized for its antimicrobial activity, reduction of metals such as arsenic (As), cadmium (Cd), copper (Cu), and iron (Fe), as well as the removal of turbidity in water [13, 14].

Under this scenario, the use of *Opuntia ficus-indica* is proposed as a coagulant and flocculant agent to enhance water quality. In this regard, the characteristics, advantages, and disadvantages associated with the use of the compound extracted from nopal in coagulation-flocculation processes are described, which are part of the water treatment systems. Thus, this work aligns with the achievement of the Sustainable Development Goals (SDGs), which promote a sustainable economy based on the exploitation of renewable natural resources to improve the quality of goods and services provided by ecosystems.

## WATER RESOURCE

Water is the essential element for life [15]. The distribution of this resource throughout the Earth, being one of the most important goods and/or services provided by nature, is divided between saltwater (97.2%) and freshwater (2.5%). The freshwater component is primarily found in snow and glaciers, accounting for 68%, while 30% is in groundwater and 1.2% is surface water, which is potentially usable [16]. It is worth noting that, in the case of Colombia, the water heritage represents 5% of the global water resources, which is six times higher than the global average, and it is mainly concentrated in the Pacific, Amazon, and Orinoco regions, accounting for 77.4%. The Magdalena-Cauca and Caribbean regions account for 13.5%, and 9.1%, respectively [17].

### Water scarcity issue

While water is a renewable resource, it could be argued that a global scarcity of water will not actually occur. However, such scarcity can be determined from different perspectives due to the relationship between resource availability and population in different territories worldwide, given the varying conditions in each of these areas. Thus, this scarcity can be defined as an emerging conflict among different populations on the planet, which has been evidenced throughout history where poor water resource management has led to the downfall of civilizations [18]. The lack of homogeneity in global water resource distribution necessitates planning and management of both natural resources and populations to enable sustainable development in each territory. This can be achieved through responsible supply and demand models that prioritize the fulfillment of human rights and economic development for each region [19]. The mismanagement of water resources has resulted in a current supply deficit for the global population, with 663 million people lacking access to clean drinking water and 2.4 billion people lacking access to basic sanitation services worldwide, leading to the deaths of 340,000 children [20].

In the case of Colombia, despite its relative water resource abundance, with precipitation in this territory accounting for 3% of the global total and 12% in South America annually, there are supply issues due to inadequate management, affecting millions of people in the Caribbean region alone [21]. The main causes of this problem are insufficient water quality and losses in distribution, particularly in the case of Medellín, where losses have reached 34% [22]. This issue is compounded by the distribution problem highlighted in CONPES 3918 for the year 2017, which reported an urban water service coverage higher than 90% while the coverage in rural areas was below 75%, with cases where water quality parameters are not met [23]. However, in Colombia, there is a surplus of water resources per capita, exceeding 80 L that represents a standard for quality of life. Therefore, it is important to properly plan it for an inclusive and sustainable distribution of this resource [21].

## Water pollution issue

Water resources can be easily contaminated primarily due to human activities such as improper waste deposition or disposal in both soils and water reservoirs. Indeed, today, human activities and population growth are responsible for the increasing pollution in different water bodies. These bodies of water can contain harmful concentrations of various metals, such as mercury (Hg), As, Cr, or selenium (Se). organic pollutants, pathogens, and nutrients, with the latter being responsible for eutrophication of water bodies [24]. Additionally, sediments and solid waste are present on the surface of these water bodies, which not only disrupts the natural conditions of water as a natural resource but also impacts life, because of they can also increase the number of contaminants contained in water since they are the vehicle of transportation of these pollutants. It should be noted that approximately 40,000,000 $m^3$ of water are discharged from rivers into the ocean each year. In each cubic meter, an average of 0.5 kg of sediments is carried, which are transported from the continents. These pollutants in oceans, lakes, rivers, or estuaries harm a wide variety of animal and plant species due to changes in their environmental conditions [24], as well as put human health at risk. A clear example is seen in Poland, where 90% of its rivers contain water unsuitable for drinking, making water distribution increasingly problematic [25].

In the specific case of Colombia, water pollution poses a significant public health issue, as 64% of the population, mainly located in the Pacific and Amazon regions, where the rural population is primarily exposed, faces a higher risk of consuming contaminated water. This situation particularly affects vulnerable population such as children and the elderly, who may experience malnutrition, diarrhea, and develop impairments because of consuming these polluted waters [16].

## Water treatment

Wastewater treatment plants (WWTPs) and drinking water treatment plants (DWTPs) are responsible for treating water for subsequent discharge into water sources or human consumption, respectively. These facilities employ treatment processes such as chemical oxidation, adsorption, coagulation and flocculation, sedimentation, filtration, and disinfection [3], as depicted in Figure 1. Among these operational units, the coagulation-flocculation process deserves special attention as it is involved in removing a significant portion of the organic load present in the water before the filtration process, being $Al_2(SO_4)_3$ one of the most used coagulant agents.

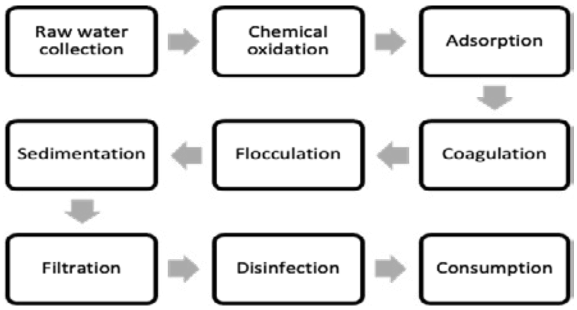


**Figure 1.** *Water purification process in a drinking water treatment plant*

DWTPs are engineered structures designed for the treatment of raw water intended for human consumption using a variety of selected processes based on water quality, geographical conditions, etc. These facilities can be classified as either rapid or slow filtration plants and aim to meet the required quality parameters according to environmental regulations [26]. In Colombia, these quality parameters and maximum allowable values or permissible ranges are regulated by Resolution 2115 of 2007, which specifies the characteristics, basic instruments, and frequency of the monitoring and surveillance system for water quality for human consumption [27]. In the Aburrá Valley, there are 13 DWTPs, including San Antonio de Prado, Rionegro, Caldas, Aguas Frías, La Ayurá, San Cristóbal, La Cascada, La Montaña, Villa Hermosa, Barbosa, Palmitas, San Nicolás, and Manantiales. Among them, Manantiales stands out as one of the most representative, with a capacity to treat

6 $m^3/s$ in the first stage and 9 $m^3/s$ in the second stage. This DWTP incorporates processes such as adsorption, coagulation-flocculation, sedimentation, filtration, disinfection, and pH stabilization, complying with legislation while generating insoluble solid waste [28, 29].

In turn, a WWTP aims to achieve compliance with regulations through different treatment stages (pre-treatment, primary treatment, biological or secondary treatment, and tertiary treatment), considering the water resource condition and legal requirements. In Colombia, these requirements are defined by Resolution 0631 of 2015 [30] for discharges into surface water bodies and sewage systems, as well as Resolution 0883 of 2018 for discharges into marine water bodies [31]. By applying these regulations, the goal is to utilize the water resource for discharge into water bodies, public sewer systems, or marine environments, or to return it to the production process according to Resolution 1207 of 2014, which governs the use of treated wastewater. In the Aburrá Valley region, there are two WWTPs: San Fernando WWTP and Aguas Claras WWTP. The latter is particularly noteworthy for its large-scale operation, treating 95% of the wastewater that used to be discharged into the Medellín River, benefiting the organisms inhabiting the river and its surroundings, and improving the conditions of the Cauca and Magdalena rivers. The treatment process of Aguas Claras WWTP includes a primary treatment for the removal of coarse waste (volume: 23,590 $m^3$, retention time: one hour), followed by a secondary treatment with a biological tank (volume: 14,250 $m^3$) divided into anoxic (25%) and aerobic (75%) zones. The effluent then proceeds to aeration tanks and secondary sedimentation tanks (8 in total, volume: 68,417 $m^3$ each), generating sludge, which is subsequently reduced by 50% through thickening tanks. The process continues with sludge stabilization and energy recovery through six reactors (volume: 8,600 $m^3$ each). Finally, the treated sludge is stored in a digested sludge tank for appropriate disposal.

## COAGULATION-FLOCCULATION PROCESS

Through the coagulation-flocculation process suspended solids can be effectively eliminated, improving the resource's characteristics, and facilitating subsequent processes [32, 33]. Coagulation is defined as the addition of organic or inorganic coagulants to destabilize colloidal particles present in water [34]. On the other hand, flocculation is defined as the contact of destabilized particles with the intention of forming aggregates (flocs) that are more susceptible to solid-liquid separation [35]. This process can be enhanced using coagulant aids, which neutralize elements that hinder the coagulation process, allowing for more efficient floc formation [32].

Optimizing the operating conditions of this process involves conducting an experimental phase using jar tests. This test requires the use of equipment typically comprising several beakers with a diameter of ~ 0.12 m and the same number of mixing paddles as beakers with a diameter of 0.05 m each [36]. The purpose of this equipment is to determine the coagulant dosage for water treatment through comparison tests between two or more samples. The time and speed of agitation can be varied to evaluate the coagulation efficiency based on the concentrations of coagulant added to each sample. In this regard, characteristics such as turbidity, color, reduction in hardness, pH, and organic load in terms of total organic carbon (TOC), biochemical oxygen demand (BOD), and chemical oxygen demand (COD), among other water characteristics, are improved, providing a systematic evaluation of this process.

There are many categories of coagulant compounds, such as iron (Fe) and aluminum (Al) salts, which belong to the inorganic coagulants and are commonly used in the coagulation-flocculation process of water. Nonetheless, they pose challenges due to the generation of sludge and their detrimental effects on water sources, increasing treatment costs due to their high toxicity [37]. A particular compound is $Al_2(SO_4)_3$, which exists in solid, granular, powder, or liquid form. The chemical formula of this compound is $Al_2(SO_4)_3 \cdot N\,H_2O$, where N refers to the number of water molecules and depends on the manufacturing method but generally ranges from 12 to 16.

$Al_2(SO_4)_3$ can react with water and form corrosive sulfuric acid ($H_2SO_4$) according to Eq. (1) [38], significantly increasing the adverse effects on water resources and consequently on living organisms, as it is a neurotoxic compound [37].

$$Al_2(SO_4)_3 + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2SO_4 \quad (1)$$

On the other hand, Al can be particularly hazardous to human health due to its bioaccumulative characteristics as it is easily assimilated by living organisms and has minimal rates of renal excretion [4]. Furthermore, its toxicological potential is associated with rapid intestinal absorption, leading to organic distribution through the bloodstream and eventual release into tissues and organs, primarily the brain, liver, and kidneys [4]. In addition, several research associates this compound with the development of degenerative diseases such as cognitive impairment, Alzheimer's disease, breast cancer, and bone diseases [5, 6].

This persistence of Al not only occurs within individual organisms but also in the aquatic environment, contributing to the deterioration of water quality as residual amounts of this compound remain in the water post-treatment [6].

However, $Al_2(SO_4)_3$ is not the only chemical compound used in the coagulation-flocculation process. Both ferric sulfate ($Fe_2(SO_4)_3$) and ferric chloride ($FeCl_3$) are viable chemical alternatives to this compound [39, 40] and are widely utilized. Although the residual Fe in the treated water using these iron salts also has associated toxicity, it is lower than that associated with Al.

Therefore, there is growing interest in finding alternatives to these salts, especially for those based on Al.

### Alternative treatment systems

Currently, there is a growing interest in identifying and analyzing natural coagulants as alternatives for water treatment, which have untapped benefits. These coagulants are environmentally friendly, easy to handle, and mainly composed of mucilages, alkaloids, tannins, polysaccharides, and proteins, with the potential to be anionic, nonionic, or cationic [41]. These biocoagulants encompass a wide range of plant-derived products such as the rain tree (*Pithecellobium saman*), *Malvaviscus arboreus*, *Heliocarpus popayanensis*, as well as starch from potato peels, Cañafístula seeds (*Cassia fistula*), fique leaves (*Furcraea sp.*), or *Aloe vera*, which could be potentially useful for this purpose [42]. These products have a high carbohydrate content and low or negligible toxicity, which is crucial for their implementation as coagulant-flocculant agents for contaminants and colloids in water treatment processes.

The most widely used biocoagulant is *Moringa oleifera*, which can remove up to 96.18% of turbidity in seawater solution, making it a highly performing natural coagulant [41]. Thus, there is a wide range of alternatives aiming to replace multivalent ions ($Al^{3+}$, $Fe^{3+}$, $Fe^{2+}$, $Mg^{2+}$, or $Ca^{2+}$) found in chemical coagulants with organic compounds that provide equally effective clarification, phosphate removal, and BOD removal, as demonstrated by the *Opuntia sp*[43]. Additionally, it is important to emphasize the need for renewable products to prevent the degradation of water resources, the overall increase in water treatment costs, and the generation of toxic byproducts.

Furthermore, it is worth noting that traditionally, in rural tropical areas, biocoagulants have been used for household purposes [44]. However, their success is not always guaranteed, and due to their specific characteristics, each case must be studied in detail. Therefore, there is a wide range of products available, such as nirmali seeds (*Strychnos potatorum*), chestnuts (*Castanea sativa*), maize (*Zea mays*), chitosan, cactus-extracted polymers, among numerous other alternatives [45].

## USE OF *Opuntia ficus-indica* IN THE TREATMENT OF CONTAMINATED WATER

The nopal cactus (*Opuntia ficus-indica*), also known as prickly pear, Indian fig, chumbera, or palera, shows promise in the coagulation-flocculation process. It is worth noting that this plant is native to the southern regions of America, specifically Mexico and the United States. Nevertheless, it has also successfully adapted to regions such as Australia, Africa, and the Mediterranean due to its remarkable adaptability, often thriving in arid zones. Nopal is renowned for its medicinal properties and has been consumed as a food product in Mexico and Brazil, indicating minimal to no toxic risk for human consumption [46, 47]. It is also considered as a medicine due to its anti-inflammatory and laxative properties. Additionally, nopal is also used for discomfort caused by excessive alcohol consumption, as well as for abdominal management, pain relief, and reducing high blood sugar levels [12].

From a physiological perspective, the plant can exhibit an arborescent, shrubby, or creeping growth habit, with a simple or bushy form. It features a well-defined woody trunk with scattered or cup-shaped branches, and both the stems and branches are jointed. The nopal plant can reach a height of up to 5 m, and its elongated pads, known as "pencas," can attain a maximum width of 50 cm and a thickness of 2 cm. They typically display an opaque green color, with some varieties having short, weak spines that are white or yellow in color. Additionally, this plant produces flowers and oval-shaped fruits with reddish, orange, or yellow coloration.

Given its properties as a natural coagulant, the mucilage can be incorporated into the coagulation-flocculation process for water treatment. This function is based on its biodegradability, low toxicity, commercial cost, relative abundance, renewability, and high efficiency, resulting in a low environmental impact compared to synthetic and inorganic polymers [48, 49]. Notably, the cost of this coagulant is around 0.16 USD/kg, whereas for $Al_2(SO_4)_3$, it is 0.36 USD/kg, being the latter 55% more expensive than the natural alternative.

Through various scientific studies, it has been established that the mucilage contains carbohydrates like D-galactose, L-arabinose, , L-rhamnose, galacturonic acid, and D-xylose, which are responsible for its behavior in the coagulation-flocculation process [50]. The mixture of these carbohydrates represents a registered molecular weight of $2.3*10^4$– $4.3*10^6$ Da [51]. The mucilage has been extensively studied as a natural or biological coagulant, with the capacity to destabilize dissolved solids through adsorption mechanisms, easily removing them due to dipole-dipole interactions. This allows colloidal particles to adhere to the main and side chains of the polysaccharides present in the mucilage of *Opuntia ficus-indica*, forming particle complexes and adsorbing a significant number of contaminants due to the high molecular weight of the polysaccharides. Therefore, coagulation is facilitated in the presence of natural electrolytes such as calcium ions ($Ca^{2+}$) or magnesium ions ($Mg^{2+}$), which enhance complex formation through their synergistic effect [49].

Among the most important applications of nopal mucilage is the removal of metals, with emphasis on $Cu^{2+}$. Although copper is an essential micronutrient for living organisms, at high concentrations ($Cu^{2+}$ > 40-50 μg/L), it cannot biodegrade and becomes a toxic and carcinogenic compound. Moreover, it can cause damage to osmoregulation mechanisms in aquatic ecosystems [13]. Similarly, As, which is commonly present in various ecosystems and natural resources, is toxic even at low concentrations. In fact, As can cause various health damages in humans, such as neoplasms, respiratory, cerebral, and vascular diseases. Currently, an estimated 40 million people worldwide consume water resources containing As [52]. Just as mucilage has been effective in metal removal, nopal has also been successful in the removal of other contaminants that are detrimental to the natural conditions of water resources. Thanks to its adsorption capacity, it is possible to achieve good results in the coagulation-flocculation process for turbidity parameters, reducing them by 70.9%; BOD by 57.2%; COD by 64.3%; chromium (Cr) by 67.4%; Fe by 98%; sulfates ($SO_4^{2-}$) by 86.2%; and chlorides ($Cl^-$) by 83.2% [51]. Table 1 presents some comparative studies on the improvement of water characteristics using mucilage from *Opuntia ficus-indica* and $Al_2(SO_4)_3$.

As observed in the table, a higher percentage of turbidity removal is achieved when using $Al_2(SO_4)_3$ compared

**Table 1.** *Aluminum sulfate ($Al_2(SO_4)_3$) vs. Opuntia ficus-indica as coagulant agentes for natural water treatment.*

| Reference | *Opuntia ficus-indica* | | | $Al_2(SO_4)_3$ | | |
|---|---|---|---|---|---|---|
| | Turbidity | pH | Water | Turbidity | pH | Water |
| Verbel et al. [47] | 83,66% | 6.41 | Magdalena River(Colombia) | 99.3% | 5,44 | Magdalena River(Colombia) |
| Flores et al. [53] | 54,2% | -- | La Peca Creek (Amazonas) | 74.7% | | La Peca Creek (Amazonas) |
| Verbel et al. [5] | 93,25% | 6.97 | Magdalena River (Colombia) | 99.8% | 5,89 | Río Magdalena River(Colombia) |
| Atupaña *et al.* [54] | 96,2% | 6.97 | BuluBulu River (Ecuador) | 95.52% | 7,08 | BuluBulu River (Ecuador) |

to the use of *Opuntia ficus-indica* mucilage. This can be attributed to the fact that the synthetic coagulant generates more hydrolyzed compounds with positive charges, allowing for the neutralization of a greater number of colloids. It is also noteworthy that the flocs formed by $Al_2(SO_4)_3$ exhibit an almost spherical shape [49].

The efficiency of removal has been demonstrated to be 93.25% with *Opuntia ficus-indica* at a concentration of 40 mg/L, with 1 min of agitation and 1 h of sedimentation, indicating its potential as a primary coagulant [5]. Furthermore, to address various issues such as the removal of heavy metals to improve water resource conditions, a complete extraction of copper ($Cu^{2+}$) has also been established with *Opuntia ficus-indica*, achieving 100% removal at a concentration of 30 mg/L in less than 5 min of reaction time [13].

**Table 2.** *Treatment of wastewater by using Opuntia ficus-indica mucilage.*

| Ref. | Type of water | Findings |
|---|---|---|
| Choudhary et al. [55] | Oil sands process-affected water | - 98% turbidity removal was found at initial pH of 7 and 8 using 1500 mg/L within 60 min.<br>- The bio-coagulant resulted in a compact sludge formation with less volume compared to aluminum. |
| Wan et al. [56] | Tailings pond water from the oil sand process industry (TPW) | - At a dose of 900 mg/L, *Opuntia ficus-indica* removed 98% of the turbidity of TPW.<br>- Acidification of TPW effluent improved dissolved organic carbon (DOC) removal significantly.<br>- The settling velocity of the flocs was 6.28 cm/min, 4.54 cm/min, and 3.01 cm/min generated by *Opuntia ficus-indica*, alum, and ferric chloride ($FeCl_3$), respectively.<br>- *Opuntia ficus-indica* showed higher arsenic (As) removal (64%) compared to alum and $FeCl_3$.<br>- *Opuntia ficus-indica* showed about 1.8 times greater adsorption capacity for activated carbon than alum. |
| Mejía-Rivas et al. [57] | Mezcal vinasse wastewater | *Opuntia ficus-indica* used as a coadyuvant, was able to remove 84% of COD through the coagulation-flocculation process. |
| Ihaddaden et al. [58] | Synthetic water with methylene blue | A mass of 0.4 g of *Opuntia ficus-indica* gave a removal of the dye of 98.99 % for an initial concentration of 90 mg/L during 19 min, at a stirring speed of 180 rpm and 40 rpm for coagulation and flocculation, respectively. |
| Sethu et al. [59] | Palm oil mill effluent | - The bio-coagulant can remove 91.2% COD, 94.4% total suspended solids (TSS) and 90.7% turbidity.<br>- The reduction of COD, TSS and turbidity by *Opuntia sp.* with okra solution improved to 93.9%, 96.1% and 93.6%, respectively, for an Opuntia powder dosage of 8 g/L, pH 9 after 240 min of reaction time. |
| Trindade et al. [60] | Wastewater with clay | - The use of 60 g of *Opuntia ficus-indica* reached 4 NTU of turbidity.<br>- The flocculation of clay in water was promoted, enabling to turn the unused material waste into a useful raw material. |
| Dkhissi et al. [61] | Vegetable oil refinery wastewater | - *Opuntia ficus-indica* showed removal percentages between 86 and 99%, 62 and 76%, and 67 and 95% for turbidity, COD, and discoloration, respectively. |
| Vargas-Solano et al. [62] | Yautepec river water | - The *Opuntia ficus-indica* mucilage (350 mg/L) had a reduction of water turbidity > 70% and a removal capacity > 90% for iron (Fe) and manganese (Mn), and > 60% for chromium (Cr) and As, and < 40% for cadmium (Cd), nickel (Ni) and lead (Pb). |
| Demim et al. [63] | Synthetic water with Eriochrome Black T (EBT) | - 1 g/L of $FeCl_3$ as a coagulant and 20 g/L of mucilage derived from cactus as a flocculant, were used resulting in a decolorization of 55.87% for a EBT concentration of 100 mg/L, a mucilage solution volume of 2 mL, and a pH level of 13. |

Regarding the elimination of As, which is ubiquitously present in the earth's crust with varying concentrations in soil and water, and is toxic to humans [56], the study conducted by Vecino et al. [52] stands out. In this study, a solution containing 1.25 mg/L of As, 4% sodium alginate ($C_6H_9NaO_7$), and 0.75 mol/L calcium chloride ($CaCl_2$) was used, with a reaction time of 5 min resulting in a 48.5% extraction of As. However, a 63% removal of As was achieved after a treatment time of 60 min [52]. In this regard, it promotes the well-being of consumers of the resource and reduces the concentrations of corrosive or toxic contaminants accumulated in different sources used for drinking water.

In Table 2, studies regarding the use of *Opuntia ficus-indica* mucilage in the treatment of water and wastewater different from natural water are compiled.

Therefore, *Opuntia ficus-indica* mucilage as a biological coagulant-flocculant can be feasible to be used, based on the observed removal percentages of turbidity, heavy metals, and organic pollutants. This can be ascribed to the polymeric bridge mechanism [59]. The adsorption capacity of this biocoagulant has also been ascribed to the carbonyl, carboxyl and hydroxyl groups that were found in the study conducted by Vargas-Solano [62] through the characterization of *Opuntia ficus-indica* mucilage for the removal of heavy metals. Demim et al. [63], in turn, associated the good results achieved for the elimination of the dye Erichrome black T by the coagulation-flocculation process with the presence of carbohydrates. However, the organic characteristics of mucilage and its biodegradability are particularly relevant in this context [50].

## Mucilage extraction

For the implementation of this alternative, one of the most important factors in conducting the test is the efficient extraction of mucilage from the nopal leaves. This is done to maximize the utilization of this plant, considering the significant yield of this complex. There are different methodologies reported in the literature based on cutting, peeling, weighing, cleaning, microwave-assisted extraction, cooling, liquefaction, filtration, precipitation, collection, and finally, lyophilization [13, 55, 58, 59, 61, 63]. Similarly, efficient mucilage removal can be achieved through size reduction, drying, grinding, and sieving processes, followed by chlorophyll extraction.

After mucilage extraction, it is necessary to optimize the amount of substance to be added to the contaminated water to facilitate an efficient coagulation-flocculation process. Additionally, the reaction time required for this mucilage concentration in the water should be evaluated. One of the most influential parameters in the efficiency of using nopal for water treatment is the quantity and quality of the extracted mucilage. Various methodologies have been established to enable the efficient and sustainable utilization of mucilage from *Opuntia ficus-indica*. According to the state of the art, certain extraction methodologies have been identified [5, 13, 47, 64]. Among them, that proposed by Ortiz and coworkers [55] can be accessible for any population and allowed to obtain a yield of 18.8% ± 2% of powdered mucilage per 100 g of dry matter with a pH of 6.1 [13]. This methodology is based on the following stages:

1. Collection of nopal leaves, which should be previously cultivated in the urban area.
2. Removal of the outer layer of the nopal by peeling, until obtaining the pulp.
3. Division of the pulp into strips of equal size.
4. Dehydration of the pulp strips at a temperature of approximately 60 °C for 48 hours.
5. Crushing of the previously dehydrated strips in a mortar to reduce them to powder.
6. Sieving of the result from the previous step.

Figure 2 presents the procedure for the most cost-effective mucilage extraction. Additionally, Table 3 lists the ranges in which mucilage concentration can be varied to optimize the coagulation-flocculation process, following the procedure established in ASTM D2035-08 standard. In turn, Figure 3 illustrates the proposed methodology for achieving high efficiency in the coagulation-flocculation process.

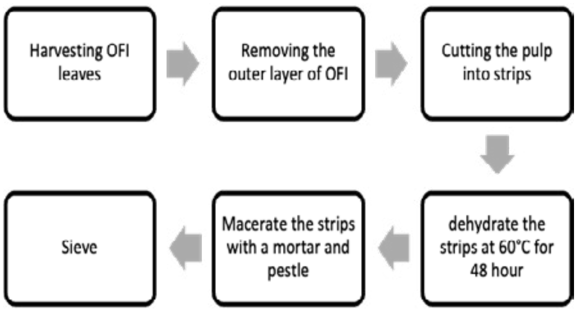


**Figure 2.** *General process for the extraction of mucilage from Opuntia ficus-indica.*

**Table 3.** *Concentration ranges for mucilage from Opuntia ficus-indica.*

| Jar N° | mg/L |
|---|---|
| 1 | 10.0 |
| 2 | 15.0 |
| 3 | 20.0 |
| 4 | 25.0 |
| 5 | 30.0 |
| 6 | 35.0 |

## Future perspectives

The *Opuntia ficus-indica* mucilage used as a coagulant-flocculant agent is a promising alternative in terms of cost-benefit factors. This is due to the versatility of the prickly pear cactus, which can grow and adapt in diverse environments. Additionally, its maintenance is not a complex task as the plant has low weekly water requirements, resulting in lower costs associated with mucilage production. Other noteworthy factors include operational ease, high efficiency, short reaction times,

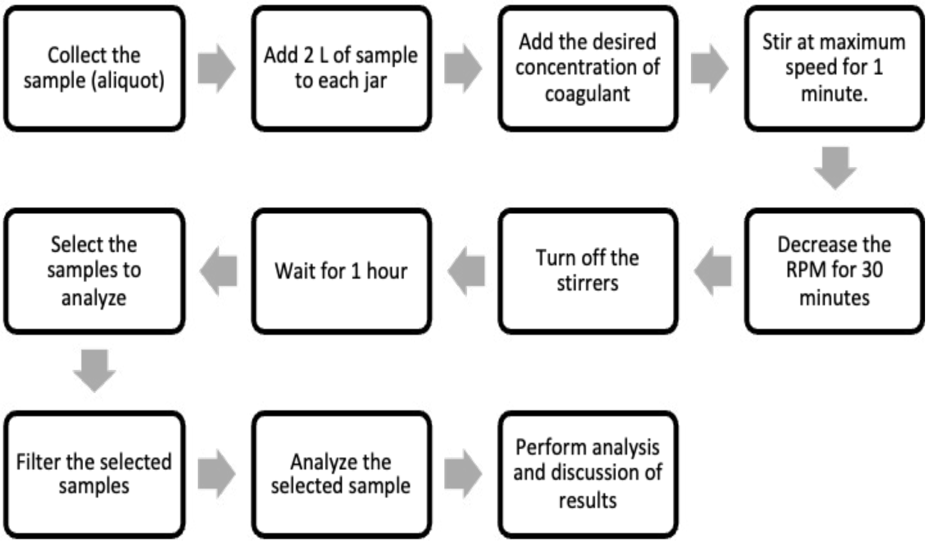


**Figure 3.** *Scheme used for the coagulation-flocculation process optimization*

and reduced sludge production [13]. It is important to highlight those substances such as $Al_2(SO_4)_3$ or $Fe_2(SO_4)_3$, which are commonly used for water treatment processes [39], not only contribute to environmental contamination and potential health hazards but also entail higher overall costs.

Furthermore, it should be noted that certain regions around the world, and specifically in Colombia, lack access to potable water services, leading to the development of improvised or artisanal systems to provide water in these underserved areas where resources are scarce [6]. These locations typically lack the financial resources to implement industrial-scale treatment processes commonly found in urban areas. Therefore, alternative approaches for treating this valuable resource need to be developed.

In this regard, the use of a product that is environmentally friendly and poses minimal to no health risks, as the toxicity of *Opuntia ficus-indica* mucilage is very low or negligible, is a promising alternative to commonly used coagulant agents [65, 66]. This characteristic results in the generation of biodegradable sludge [13, 50]. leading to lower treatment costs and greater applicability for producing products such as fertilizers or even biodiesel. For example, in the United States, approximately 7,200,000 tons of sludge are generated in WWTPs annually, with 49% being used for soil improvement, 45% sent to landfills, and 6% utilized for other purposes. It is important to highlight that these figures would significantly decrease in developing countries due to limited investments in sludge treatment and disposal, and the final disposal of such sludge often occurs in sanitary landfills [65] or rivers.

## CONCLUSIONS

The use of inorganic compounds such as $Al_2(SO_4)_3$, $Fe_2(SO_4)_3$, and $FeCl_3$, among others, during the coagulation-flocculation process entails high economic demands over time, as well as widespread contamination of humans, aquatic ecosystems, and the living organisms inhabiting them, due to the associated toxicity of Al and Fe. In this scenario, it becomes necessary to use other alternatives and more sustainable coagulant agents, such as the mucilage derived from *Opuntia ficus-indica*.

Although $Al_2(SO_4)_3$ can exhibit a higher percentage of turbidity removal, *Opuntia ficus-indica* mucilage serves as a non-specific biocoagulant, as its entire composition (carbohydrates, polysaccharides, non-polysaccharides, electrolytes, etc.) is responsible for the coagulation-flocculation process. This enables a facilitated adsorption mechanism and results in a lower volume of sludge, which is compact and easily removable, thereby reducing the treatment costs, representing an affordable treatment option from the cultivation of the plant to its usage, making it economically competitive.

Moreover, the use of prickly pear cactus in the coagulation-flocculation process contributes to socioeconomic well-being by achieving significant removal rates of heavy metals and other chemical contaminants, while also exhibiting low toxicity. This approach promotes sustainable alternatives and a widespread improvement of water resource quality.

In this regard, nopal mucilage emerges as an important alternative to chemical coagulants, aligning with the Sustainable Development Goals (SDGs), particularly SDG 6, which focuses on improving water quality. By utilizing nopal mucilage, compliance with established regulations can be achieved while simultaneously advancing towards the SDGs.

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