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Review

Prospects and challenges of utilizing sugarcane bagasse as a bio-coagulant precursor for water treatment

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ABSTRACT

Sugarcane bagasse is an abundant and renewable agricultural waste material generated by the sugar industry worldwide. The use of sugarcane bagasse as a bio-coagulant precursor in water treatment is an eco-friendly and cost-effective approach that has shown great potential. This article reviewed the prospects and challenges of utilizing sugarcane bagasse as a bio-coagulant precursor for water treatment. The article reviewed past studies and explored the properties and chemical composition of sugarcane bagasse and the bioactive compounds that can be extracted from it, as well as their potential coagulation performance in water treatment. It was observed that there are few studies that have been published on the subject. The effectiveness of sugarcane bagasse-based coagulants varies depending on several factors, such as pH, temperature, and water quality parameters. However, the lack of standardization in the production of sugarcane bagasse-based coagulants is a challenge that needs to be addressed. Additionally, the optimization of extraction and processing methods to enhance the effectiveness of sugarcane bagasse-based coagulants needs to be investigated further. In conclusion, the use of sugarcane bagasse as a bio-coagulant precursor holds great promise for the future of sustainable water treatment. The potential for sugarcane bagasse to be used as a bio-coagulant precursor highlights the importance of exploring alternative and sustainable materials for water treatment.

1. Introduction

Water is a fundamental element for sustaining life and serves as a crucial commodity for various sectors such as agriculture, energy production, and manufacturing [1,2]. Nevertheless, the global demand for water is steadily rising due to factors such as population growth, urbanization, and industrialization, resulting in water scarcity in numerous regions across the globe [3]. According to projections by the United Nations, by 2025, approximately 50% of the world's population will be residing in areas where water scarcity is a significant concern [4,5]. Water scarcity is not only a threat to human health but also to food security, economic development, and the environment [6,7]. Furthermore, the quality of water is being compromised due to pollution stemming from diverse origins, such as agricultural runoff, industrial discharges, and domestic sewage. These contaminants can have detrimental effects on water resources, making it imperative to address water pollution as a critical environmental concern [8–10]. To address these challenges, it is crucial to develop sustainable and economically viable

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approaches for water treatment.

Coagulation is a commonly employed technique in water treatment, involving the introduction of a coagulant into water to cause the aggregation and destabilization of suspended particles. This process leads to the formation of larger aggregates that can be effectively separated through sedimentation or filtration methods [11]. Compared to other water treatment techniques, coagulation has several merits [12]. It is a relatively inexpensive water treatment technique compared to other methods such as reverse osmosis or UV disinfection [13]. The cost of the coagulants used in the process is relatively low, and the equipment required for coagulation is simple and requires minimal maintenance [14,15]. Coagulation can be used to treat a wide range of water sources, including surface water, groundwater, and wastewater [16]. It can effectively remove suspended solids, bacteria, and other contaminants, making it suitable for use in various industries. Coagulation can significantly improve the quality of water by reducing the amount of suspended solids, turbidity, and other impurities [17]. This not only makes the water safer to drink but also improves its aesthetic appeal. It is a highly efficient water treatment technique, with the ability to remove up to 99% of suspended solids from water [18]. It is also a fast process, requiring only a short retention time before the water is ready for further treatment or distribution. In addition, coagulation does not produce any harmful by-products or waste, making it an environmentally friendly water treatment technique [19]. A schematic representation of this process is depicted in Fig. 1.

Conventional coagulants, such as aluminium and iron salts, are effective but have several drawbacks, including a high cost, potential health hazards, and environmental concerns [21]. Lately, there has been a surge of interest in employing bio-coagulants for various water treatment applications such as chitosan, *Moringa oleifera*, and algal polysaccharides, which are derived from natural sources and have several advantages over conventional coagulants [21–23]. They are environmentally friendly. Unlike chemical coagulants, they do not contain hazardous chemicals or produce toxic by-products. They are often cheaper than chemical coagulants, especially when locally sourced. They can be obtained from plants, animals, and microorganisms, which are abundant in nature and easily accessible [24,25]. However, the use of bio-coagulants also has some limitations. They may not be as effective as chemical coagulants in some situations, and their performance may vary depending on the water source and the specific bio-coagulant used [26].

One potential and underutilized source of bio-coagulants is sugarcane bagasse, which is a by-product of the sugar industry and is available in large quantities worldwide. Sugarcane bagasse, the fibrous residue that remains after the juice is extracted from sugarcane, is a potential precursor for bio-coagulant production due to its abundance, low cost, and rich composition of lignocellulosic compounds [27]. Sugarcane bagasse-based bio-coagulants have shown great potential in water treatment, effectively removing suspended particles, organic matter, and heavy metals from various types of water and wastewater. In addition, the use of sugarcane bagasse as a precursor for bio-coagulant production has several environmental and economic benefits, including reduced waste generation, reduced dependence on conventional coagulants, and increased revenue for the sugar industry.

The aim of this article is to provide an overview of the potential of sugarcane bagasse as a source of bioactive compounds for the production of bio-coagulants in the water treatment industry. The article aims to explore the properties and chemical composition of sugarcane bagasse and the bioactive compounds that can be extracted from it, as well as their potential coagulation performance in water treatment. Overall, the aim of the article is to provide insights into the prospects and challenges of utilizing sugarcane bagasse as a bio-coagulant precursor and to stimulate further research and development in this area. The article seeks to contribute to the growing body of knowledge on sustainable and eco-friendly water treatment technologies that can help meet the increasing demand for clean and safe drinking water while minimizing environmental impacts.

2. Sugarcane bagasse

Sugarcane bagasse is a by-product of the sugar industry and is generated during the processing of sugarcane into sugar or ethanol. It is composed of the fibrous residue remaining after juice extraction, including crushed stalks and leaves. Sugarcane bagasse is abundant and readily available, making it an attractive raw material for various applications. The global production of sugarcane bagasse is estimated to over 700 million tons per year, with Brazil and India being the largest producers [28]. Other sugarcane-producing countries such as China, Thailand, and Pakistan also generate significant amounts of sugarcane bagasse. The abundance of sugarcane bagasse is due to the fact that sugarcane is a fast-growing crop, and a large amount of it is cultivated worldwide. In addition, the sugar industry is constantly expanding, resulting in a consistent supply of sugarcane bagasse. As sugarcane bagasse is a waste material generated during the production of sugar and ethanol, it is readily available at a low cost, which makes it a desirable feedstock for many applications.

Sugarcane bagasse is a fibrous material that is typically light brown in colour and has a rough surface. It has a high moisture content, ranging from 45% to 70%, depending on the drying method and storage conditions. Sugarcane bagasse is composed mainly of lignocellulosic compounds, including cellulose, hemicellulose, and lignin, which account for approximately 40–50%, 20–30%, and 20–25% of the dry weight, respectively [29]. Other minor components include ash, extractives, and proteins. The chemical composition of sugarcane bagasse varies

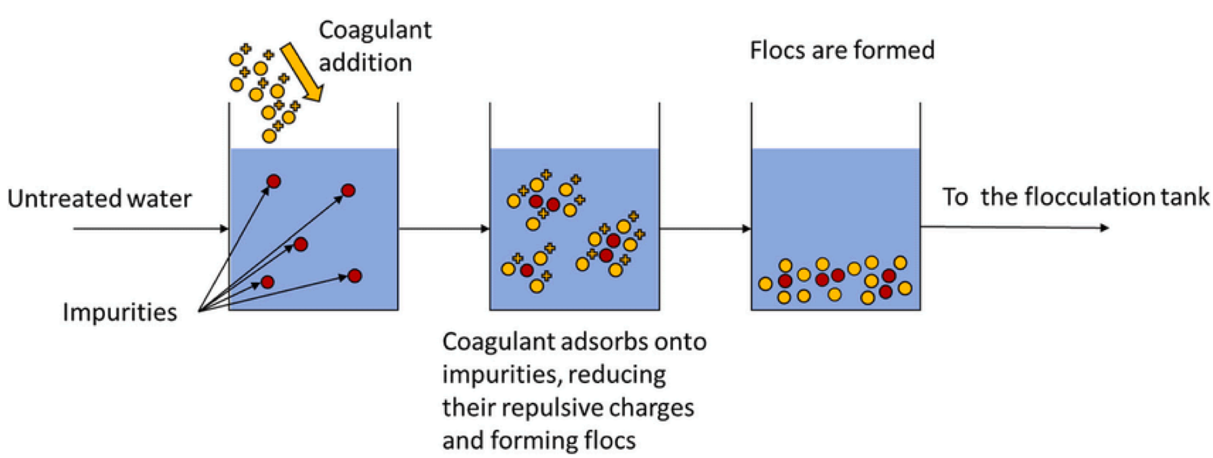

Fig. 1. A schematic diagram of the coagulation process employed during water treatment [20].

depending on several factors such as the age and variety of sugarcane, harvesting season, and processing methods [30,31].

The structure of sugarcane bagasse is complex and hierarchical, consisting of various levels of organization, including macroscopic, microscopic, and molecular levels [32]. At the macroscopic level, sugarcane bagasse is composed of bundles of fibres, which are held together by a matrix of parenchyma cells. At the microscopic level, the fibres are composed of microfibrils of cellulose, which are embedded in a matrix of hemicellulose and lignin. The microfibrils have a diameter of approximately 3–4 nm and a length of several micrometres [33,34]. At the molecular level, cellulose is a linear polymer of glucose units, hemicellulose is a branched polymer of various sugar units, and lignin is a complex polymer of phenylpropane units [35,36]. Cellulose is the main component of sugarcane bagasse, accounting for approximately 40–50% of the dry weight [37]. It is a linear polymer of glucose units that provides structural support to the plant cell walls. Hemicellulose is the second most abundant component, accounting for 20–30% of the dry weight. It is a branched polymer of various sugar units that provides flexibility and elasticity to the plant cell walls. Lignin is the third most abundant component, accounting for 20–25% of the dry weight. It is a complex polymer of phenylpropane units that provides rigidity and hydrophobicity to the plant cell walls [38]. Ash, extractives, and proteins are minor components that account for less than 5% of the dry weight [39].

One practical consideration for utilizing sugarcane bagasse as a bio-coagulant precursor, despite its widespread use as fuel in the sugar industry, is the availability of sugarcane bagasse in different regions of the world. A significant amount of bagasse obtained from chewed sugarcane that is not processed in factories ends up as waste in the environment. However, while it is common for sugar industries to use bagasse as their primary fuel, it is not always the case that they exhaust their entire bagasse supply before the end of a crushing season. The utilization of sugarcane bagasse as a fuel source in sugar industries can vary depending on several factors, including the scale of operations, the technology employed, and the duration of the crushing season [40].

3. A review of previous studies

Few researchers have studied the utilization of sugarcane bagasse as a precursor for the synthesis of bio-coagulant. Some of their observations are discussed in this section. The summary of their observations is stated in Table 1. It can be observed that the extraction technique, concentration of the extracting solvent, and operating parameters such as temperature and pH affects the yield of the bio-coagulant being extracted. In addition, the operating variables such as the pH and coagulant dosage affects the efficacy of the bio-coagulant.

In a bid to obtain alternatives to chemical coagulants, Zaidi, Muda, Rahman, Sgawi and Amran [41] studied the efficiency of four plant-based materials (chestnut peel, maize cob, whole chestnut, and sugarcane bagasse) as suitable coagulants for the treatment of raw water. The precursors were treated with 2 M sodium hydroxide. It was observed that the bagasse-based coagulant gave the highest yield in comparison with other coagulants, at 79.5%. It was also recorded that the bagasse-based coagulant gave the highest turbidity removal in comparison with the other coagulants, 97.3%, obtained at pH 7.5 [41]. In a recent study, Nippes, Macruz, Fernandes and Gimenes [42] utilized coagulation-flocculation/adsorption process for the treatment of vinasse, a distillery by-product, using sugarcane bagasse-based activated carbon agglomerated with alumina. The bio-coagulant which was extracted with the aid of $AlCl_3{\cdot}6H_2O$/ NH_4OH after which it was activated using NaOH. The bio-coagulant as shown in Fig. 2, was observed to have an irregular structure with large number of pores and cavities of different sizes. The study recorded a decrease in total organic carbon by 76%, chemical oxygen demand by 72%, turbidity by 96%, and colour by 73% [42].

A study previously published compared the effectiveness of sugarcane bagasse fly ash-based coagulant and two different chemical coagulants, ferrous chloride and ferric chloride, for the treatment of dye and pigment wastewater. Their findings revealed that the bio-coagulant pre-treated with 10% sulphuric acid was more effective than the chemical coagulant for the reduction of chemical oxygen demand, colour, turbidity, and total suspended solids from the wastewater [43].

The effects of two acids used for the pre-treatment of sugarcane bagasse ash were compared in a study published by Water Supply [44]. The acids (4 M each), hydrochloric acid, and sulphuric acid were used to treat the precursor in a solid-to-liquid ratio of 1:10 before being utilized as a coagulant. It was observed that the hydrochloric acid-based coagulant was more effective than the sulphuric acid-based coagulant as the former had a higher surface area and reduced the turbidity of a river water sample by 99.9% [44]. In another study, Bahrodin, Zaidi, Kadier, Hussein, Syafiuddin and Boopathy [45] prepared a bio-coagulant from sugarcane bagasse. The researchers compared the effects of two different solvents for the treatment stage, i.e., sulphuric acid and sodium hydroxide, and the effects of concentration, temperature, and time for the pre-treatment. It was observed that, based on the solvents used, 8% NaOH solution, at 120 °C for two hours gave the highest polysaccharide content. The bio-coagulant was utilized for the treatment of kaolin-based synthetic wastewater. A maximum turbidity removal of 95% was recorded at pH 4 and 50 mg/L coagulant dosage [45].

In a recent study published in the Science of the Total Environment, the authors opined that the functional group(s) responsible for the effectiveness of any bio-coagulant may vary based on some parameters, such as charge neutralization and bridging [46]. However, they noted that functional groups such as the hydroxyl and carboxyl groups are essential in the workings of any bio-coagulant. These functional groups have been observed to be abundant in sugarcane bagasse, as stated by various researchers [47], which makes sugarcane bagasse a suitable precursor for the production of bio-coagulants.

4. Potential applications of sugarcane bagasse-based bio-coagulants

Sugarcane bagasse-based bio-coagulants have shown great potential in various industries for water treatment purposes due to their effectiveness, cost-effectiveness, and eco-friendly properties. Some of the potential applications of sugarcane bagasse-based bio-coagulants in different fields are documented in this section.

Municipal water treatment plants can benefit from using sugarcane bagasse-based bio-coagulants as they are effective in removing suspended solids, organic matter, and turbidity from the water. Bio-coagulants can also help in reducing the formation of disinfection by-products, which are harmful to human health. The use of bio-

Table 1
Summary of the process for studies involving sugarcane bagasse based bio-coagulants.

Solvent used	Yield of bio-coagulant (%)	SSA (m^2/g)	Optimum dosage (mg/L)	Optimum pH	Coagulation efficiency (%)	Refs.
NaOH	79.5	–	90.0	7.5	97.30	[41]
$AlCl_3{\cdot}6H_2O$/ NH_4OH	–	913.0	150	–	96.06	[42]
H_2SO_4	–	–	–	–	90.00	[43]
HCl or H_2SO_4	–	–	–	8.0	99.90	[44]
NaOH or H_2SO_4			50	4.0	95.00	[45]

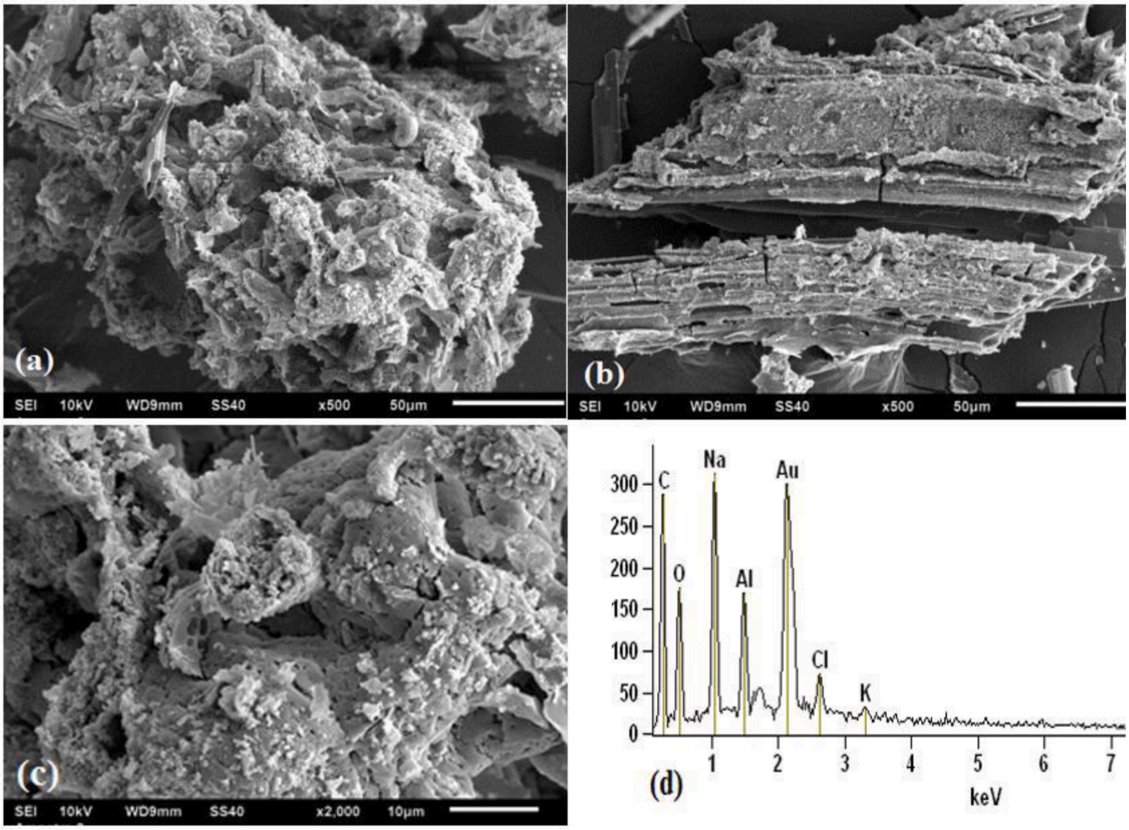

Fig. 2. SEM-EDX of sugarcane bagasse bio-coagulant [42].

coagulants can also lead to a reduction in sludge production, thus reducing the cost of sludge disposal [48,49]. Sugarcane bagasse-based bio-coagulants can be used in the treatment of industrial wastewater as well. The bio-coagulants can effectively remove suspended solids, organic matter, and heavy metals from the wastewater. This can help industries comply with environmental regulations and reduce the environmental impact of their operations. The low-cost of bio-coagulants can also provide industries with a cost-effective alternative to traditional chemical coagulants [50]. Sugarcane bagasse-based bio-coagulants can also be used in agriculture for water treatment purposes. Bio-coagulants can help in the removal of suspended solids, organic matter, and pesticides from irrigation water. The use of bio-coagulants can help in improving soil health and plant growth by reducing the amount of contaminants in the irrigation water. This can lead to higher crop yields and better-quality produce [51].

The paper and pulp industry can also benefit from using sugarcane bagasse-based bio-coagulants. Bio-coagulants can help in the removal of lignin, a major contaminant in the paper and pulp industry, from the wastewater. The use of bio-coagulants can lead to a reduction in the amount of chemicals used in the industry, reducing the environmental impact of the industry [52]. Sugarcane bagasse-based bio-coagulants can also be used in the mining industry for water treatment purposes. The bio-coagulants can help in the removal of suspended solids, heavy metals, and other contaminants from the wastewater generated during mining operations [53,54]. The textile industry is another industry that can benefit from using sugarcane bagasse-based bio-coagulants. Bio-coagulants can help in the removal of suspended solids, colorants, and other contaminants from the wastewater generated during textile production [55,56].

The food and beverage industry can also benefit from using sugarcane bagasse-based bio-coagulants. Bio-coagulants can help in the removal of suspended solids, organic matter, and other contaminants from the wastewater generated during food and beverage production [57]. The pharmaceutical industry can also benefit from using sugarcane bagasse-based bio-coagulants. Bio-coagulants can help in the removal of suspended solids, organic matter, and other contaminants from the wastewater generated during pharmaceutical production [24]. The aquaculture industry can also benefit from using sugarcane bagasse-based bio-coagulants. Bio-coagulants can help in the removal of suspended solids, organic matter, and other contaminants from the water used in aquaculture operations. The use of bio-coagulants can help in improving water quality, reducing the risk of disease, and increasing the productivity of the aquaculture operations [58–60].

5. Challenges and opportunities

While the use of sugarcane bagasse-based bio-coagulants has many potential benefits, there are also some challenges and opportunities associated with scaling up production. These challenges and opportunities are graphically represented in Fig. 3.

- Availability of raw materials: One of the main challenges in scaling up the production of sugarcane bagasse-based bio-coagulants is the availability of raw materials. Sugarcane bagasse is a by-product of sugarcane processing, and its availability may be limited depending on the location and season as it is a fuel source for the industry. Therefore, it is important to establish reliable supply chains and storage systems to ensure a steady supply of raw materials.
- Standardization of production: The production of sugarcane bagasse-based bio-coagulants can vary depending on the source of bagasse, the processing methods used, and other factors. Standardizing production methods and ensuring consistent quality can be a challenge, but it is necessary to ensure the effectiveness of the bio-coagulants and to meet regulatory requirements.
- Cost-effectiveness: While sugarcane bagasse-based bio-coagulants are generally cost-effective compared to synthetic coagulants, the

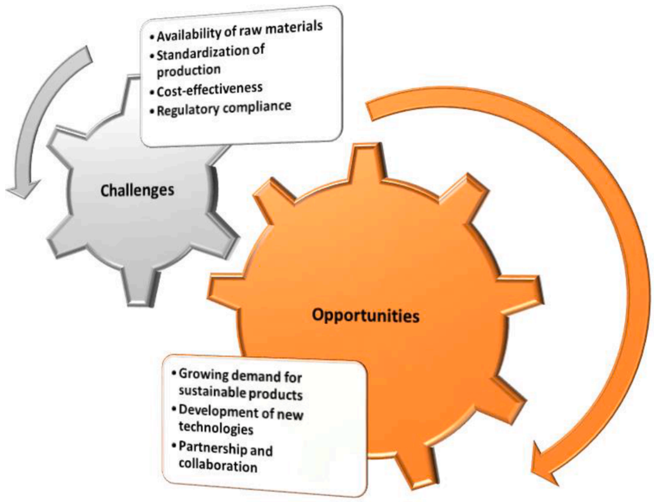

Fig. 3. Challenges and Opportunities of Utilizing sugarcane bagasse as a bio-coagulant precursor.

cost-effectiveness may vary depending on the scale of production and the availability of raw materials. The cost of production can also be affected by the need for specialized equipment and skilled labour.

- Regulatory compliance: The production and use of bio-coagulants are subject to regulatory requirements and standards. Ensuring compliance with these regulations can be a challenge, especially in different regions with varying regulations. Companies need to be aware of the regulatory requirements and ensure that their products meet the standards set by the authorities.

Some of the opportunities include:

- Growing demand for sustainable products: The demand for sustainable and eco-friendly products is growing, and the market for sugarcane bagasse-based bio-coagulants is expected to expand in the coming years [61,62]. Companies that can meet this demand by offering high-quality and cost-effective products are well-positioned to succeed in this market.
- Development of new technologies: As the demand for sugarcane bagasse-based bio-coagulants grows, there will be opportunities for the development of new technologies and innovations that can improve production efficiency and product quality. For example, new processing methods or equipment could be developed to improve the extraction of active ingredients from sugarcane bagasse.
- Partnership and collaboration: Scaling up the production of sugarcane bagasse-based bio-coagulants will require partnerships and collaboration between different stakeholders, including sugarcane processing companies, water treatment companies, and government agencies. These partnerships can help to establish reliable supply chains, improve production efficiency, and ensure that the products meet regulatory requirements. Governments can provide funding and regulatory support, while private companies can bring their expertise in production and marketing. These partnerships can help to accelerate the development and adoption of sustainable solutions for water treatment.

6. Future prospects

The production and use of sugarcane bagasse-based bio-coagulants are relatively new and emerging fields, and there is still much to learn about these products. As such, there are several avenues for future research and development that could help to improve the quality and efficacy of these bio-coagulants.

- Optimization of production methods: One area for future research is the optimization of production methods for sugarcane bagasse-based bio-coagulants. This could include developing more efficient and cost-effective production processes, exploring the use of different types of sugarcane bagasse, and refining the extraction and purification methods.
- Performance evaluation: Another area for future research is the evaluation of the performance of sugarcane bagasse-based bio-coagulants in different water treatment applications. This could involve testing the products in different types of water (such as industrial wastewater or agricultural runoff) and under varying conditions (such as different pH levels or temperatures).
- Mechanisms of action: The mechanisms of action of sugarcane bagasse-based bio-coagulants are not yet fully understood, and future research could help to elucidate these mechanisms. This could involve studying the chemical and physical properties of the bio-coagulants and their interactions with contaminants in water.
- Environmental impacts: Sugarcane bagasse-based bio-coagulants are generally considered to be more environmentally friendly than traditional chemical coagulants. However, there is still a need to evaluate the environmental impacts of these products throughout their lifecycle, including their production, use, and disposal.
- Scale-up of production: As the demand for sustainable water treatment solutions grows, there is a need to scale up the production of sugarcane bagasse-based bio-coagulants. Future research could focus on developing strategies for scaling up production while maintaining product quality and ensuring regulatory compliance.
- Cost-effectiveness: One of the key challenges for the widespread adoption of sugarcane bagasse-based bio-coagulants is their cost-effectiveness compared to traditional chemical coagulants. Future research could explore ways to reduce the cost of production while maintaining product quality and performance.

7. Conclusion

In conclusion, the use of sugarcane bagasse as a bio-coagulant precursor has shown significant potential as an eco-friendly and cost-effective approach to water treatment. The biodegradability and abundance of sugarcane bagasse make it a sustainable alternative to conventional coagulants. Furthermore, the utilization of sugarcane bagasse for coagulant production presents an opportunity for sugar industries to diversify their revenue streams and minimize waste production. However, there are still some challenges that need to be addressed in the utilization of sugarcane bagasse as a bio-coagulant precursor. The lack of standardization in the production of sugarcane bagasse-based coagulants is one issue that needs to be resolved. Additionally, the optimization of extraction and processing methods to enhance the effectiveness of sugarcane bagasse-based coagulants needs to be investigated further. Overall, the use of sugarcane bagasse as a bio-coagulant precursor holds great promise for the future of sustainable water treatment. Further research and development in this field are necessary to overcome the challenges and fully exploit the benefits of this material.

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Compliance with ethical standards

This article does not contain any studies involving human or animal subjects.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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