Environmental Advances 13 (2023) 100421

Contents lists available at ScienceDirect

Environmental Advances

journal homepage: www.sciencedirect.com/journal/environmental-advances

The potential and constraints of replacing conventional chemical coagulants with natural plant extracts in water and wastewater treatment

Denzil Diver [a,*], Innocent Nhapi [a], Walter Rutendo Ruziwa [b]

[a] Department of Environmental Engineering, School of Engineering Sciences and Technology, Chinhoyi University of Technology, Private Bag 7724, Chinhoyi, Zimbabwe
[b] Department of Fuels and Energy, School of Engineering Sciences and Technology, Chinhoyi University of Technology, Private Bag 7724, Chinhoyi, Zimbabwe

ARTICLE INFO

Keywords:
Chemical coagulant
Coagulation
Natural coagulant
Turbidity
Water quality
Water treatment

ABSTRACT

Coagulation is a vital stage in treating contaminated water using coagulants that can be either synthetic or natural. Currently, water is being treated by water treatment plants that use aluminum- or iron-based salts and synthetic polymers for coagulation. However, these synthetic coagulants have flaws, including the production of large amounts of chemical sludge, considerable effects on the pH of the purified water, relatively expensive to use, and potentially toxic effects on the environment. The potential and constraints of replacing chemical coagulants with natural plant extracts for water treatment are reviewed in this paper. Various natural coagulants previously investigated for the removal of heavy metals, turbidity, pathogens, and other contaminants from surface and synthetic water were analyzed based on dosage rates, active ingredients responsible for coagulation, and extraction methods among other criteria. A comparative analysis was performed in studies in which both conventional chemical coagulants and natural plant extracts were used for water treatment. Various studies have shown that it is possible to replace chemical coagulants with plant-based extracts. It has been demonstrated that it is possible to replace chemical coagulants with natural plant-based extracts because seed extracts such as those of fenugreek can achieve turbidity removal efficiencies as high as 98% as compared to 85% for alum. The use of natural coagulants may be beneficial for water treatment plants because they may produce less sludge than chemical coagulants; this increases environmental sustainability while decreasing the cost of handling sludge. They are less toxic than chemical coagulants and do not pose any adverse threats to the environment; therefore, they are a safer alternative. However, studies are needed on how these plant-based coagulants can be commercialized in the same way that chemical coagulants are readily available.

1. Introduction

Poor access to adequate, clean, and safe water is one of the greatest problems in global development (Pandey *et al.*, 2021). In 2020, approximately 122 million people were getting water directly from surface water sources (UNICEF/WHO, 2021). In 2021, about 2.2 billion people did not have safely managed drinking water services (World Bank, 2021).

Water can be contaminated by natural or anthropogenic sources of pollutants (Ojha, 2020). Many anthropogenic activities occurring in the environment have increased the contamination of available water resources (Fernando *et al.*, 2018). Moreover, an increase in population has accelerated urbanization, economic growth, and efforts to lessen poverty, resulting in intensified food production, resource mining, and industrial development. The increase in population density in urbanized areas has escalated environmental pressure from agricultural and industrial practices and waste disposal habits (Boelee *et al.*, 2019). When groundwater flows through the pores of sedimentary rocks and various soils and infiltrates them, it can contaminate the water through natural processes by mixing it with various natural substances, including iron, nitrate, arsenic, and fluoride. Consequently, high concentrations or undesirable quantities of naturally occurring compounds can contaminate groundwater, the consumption of which can cause severe health risks (Ali & Ahmad, 2020).

In both developed and developing countries, the challenges of water contamination are mainly due to chemical exposure, which includes, but is not limited to agricultural sources (Sharma & Bhattacharya, 2017). Contaminants such as insecticides, herbicides, pesticides, chemical fertilizers, heavy metals (e.g., mercury and lead), and hazardous chemicals mainly emanate from agricultural and industrial activities (Bekele &

* Corresponding author.
E-mail address: denzildiver20@gmail.com (D. Diver).

https://doi.org/10.1016/j.envadv.2023.100421
Received 18 May 2023; Received in revised form 19 August 2023; Accepted 14 September 2023
Available online 15 September 2023

Yegrem, 2021; Ashbolt, 2004; Fawell *et al.*, 2001). Disposal of batteries, diesel fuel, and household chemical wastes, such as oils, medicines, antiseptics, and paint solvents, can also result in groundwater contamination and severe health challenges (Neksumi *et al.*, 2022; Kass *et al.*, 2005; Anwar & Yaqout, 2003). Furthermore, the release of chemicals from wastewater can cause groundwater pollution. Riverbeds and wetlands are also at risk because of rising sediment impoundments and the presence of persistent and hazardous contaminants. Such pollution can persist even after the sources have stopped producing pollutants (Edokpayi *et al.* 2017).

Globally, at least two billion people use a drinking water source with fecal contamination, causing approximately 485,000 diarrheal deaths each year (WHO, 2019). The pollution of drinking water can result in high mortality and morbidity due to waterborne diseases such as typhoid, cholera, diarrhea, dysentery, hepatitis, and many protozoan and helminth infections (Pal *et al.*, 2018; Aryal *et al.*, 2012). Consumption of water that contains pathogens or elements that could be toxic can result in health impacts that range from discomfort to death (UNEP, 2016).

Raw water often requires treatment to make it potable. If the water originates from ground sources via mountain springs, the water quality is usually good, and in most cases, only disinfection is sufficient (Dursun & Sarcan, 2022). However, suspended particles are of great significance if the water is from a surface water supply such as a river, lake, or dam. Various techniques to remove suspended particles include the introduction of coagulants and the use of membranes (Owodunni *et al.*, 2023).

Owing to potential disturbances with downstream purification processes and adverse impacts on consumer acceptance, effective turbidity reduction is one of the main objectives in the treatment of drinking water. Turbidity removal during water treatment has two purposes. The removal of turbidity results in the removal of some microbes, while reducing the levels of organic matter and other particles, which increases the effectiveness of downstream treatment processes (Soros *et al.*, 2019). The removal of heavy metals is also of significant importance because they can be harmful and dangerous to consumer health, as excessive quantities of copper can be toxic and carcinogenic (Kahlson & Dixon, 2022). Bacterial removal is an important process in water treatment because infectious diseases caused by bacteriological agents are the most common and widespread health risks associated with drinking water (WHO, 2017; Mcallister, 2005).

Water turbidity can be reduced and removed using several standard techniques, including precipitation, adsorption, flotation, ion exchange, membrane filtration, and biological and electrolytic processes (Rajoria *et al.*, 2022). The process of turbidity elimination in the form of suspended and colloidal debris and dissolved matter to generate drinkable water from the majority of raw water sources requires the use of a coagulant during the coagulation-flocculation stage of water treatment operations. Coagulants and flocculants exist in a variety of forms and are used in conventional water treatment processes. These can be grouped into inorganic coagulants, such as aluminum and ferric salts; synthetic organic polymers, such as polyacrylamide derivatives and polyethylene imine; and natural coagulants, which can be obtained from microorganisms, plants, and animal tissues (Halder, 2021; Vijayaraghavan *et al.*, 2011).

In recent years, there has been significant interest in the use of natural coagulants (Amran *et al.*, 2022; Alenazi *et al.*, 2020;Mumbi *et al.*, 2018; Unnisa and Bi, 2018). Natural coagulants are biodegradable, making them a potentially sustainable option for water treatment (Agarwal & Saini, 2022). According to Makarfi *et al.* (2022), the utilization of plant-derived natural materials of plant origin to treat turbid raw water is not a new concept. Natural organic polymers have been used as coagulants and coagulant aids for water with high turbidity in China, India, and Africa for more than 2,000 years (Freitas *et al.*, 2018). Various plants such as *Moringa oleifera* seeds have been identified as natural coagulants (Nhut *et al.*, 2021; Pandey *et al.*, 2020; Hussian *et al.*, 2012; Saulawa *et al.*, 2011; Okuda *et al.*, 1999), Nirmali seeds (Alenazi *et al.*, 2020), and Cactus (Choudhary *et al.*, 2018).

The advantages of using natural coagulants for water treatment include low coagulant cost, biodegradability, production of lower sludge volume compared to chemical coagulants, and that they are easily obtainable (Kristianto *et al.*, 2018). In a study carried out by Hadadi *et al.* (2022), natural coagulants *Moringa oleifera* (MO) seeds, *Pinus halepensis* seeds (PHS), *Opuntia ficus indica*(OFI), and Algerian *Aloe vera* (AV) produced sludge volumes of 25±1 mL/L, 30± 1 mL/L, 26± 1 mL/L, and 22 ±1 mL/L, respectively, which were less than the sludge volumes produced by chemical coagulants ferric chloride and alum of 52±1 mL/L and 62± 1 mL/L, respectively. These coagulants are derived from plant materials; therefore, the byproducts are organic and biodegradable, making their use environmentally friendly (Hadadi *et al.*,2022).In terms of cost, a study conducted in India by Thirugnanasambandham & Karri (2021) revealed that natural coagulant *Azadirachta indica A. Juss* had lower operating costs ($USD 0.56/m^3) than alum ($USD 1.73/m^3) for treating urban wastewater. Despite these advantages, the level of acceptance of natural coagulants for water and wastewater treatment plants has hitherto remained low (Ang & Mohammad, 2020). This is mainly because of a lack of industrial confidence in adopting natural coagulants owing to concerns about the efficiency and consistency of these coagulants when they are used for water treatment on a large scale. Therefore, this study aimed to investigate the potential and constraints of replacing conventional chemical coagulants with natural plant extracts for water treatment. These issues will be discussed in the following sections: coagulation and flocculation processes in water treatment, classification of coagulants, classification of natural plant extracts according to the removal of contaminants, criteria for analysis of natural coagulants, coagulation performance of conventional chemical coagulants compared to coagulants derived from plant extracts, potential constraints of using natural plant extracts for water treatment, and opportunities and drawbacks for the commercialization of natural coagulants. These sections will aid in providing an overall understanding of how water is treated so that it is potable and the role of coagulants in the purification of water in removing various contaminants. The criteria for analyzing coagulants are important as they help in selecting coagulants that are appropriate for a specific water treatment setup and for water with different concentrations of contaminants.

2. Coagulation and flocculation processes in water treatment

Coagulation and flocculation processes are regularly used in the treatment of drinking water (Maćczak *et al.*, 2022)and industrial effluents (Teh *et al.*, 2016). In an aqueous medium, the majority of solids or suspended particles are smaller and have negative charges. Consequently, the particles must group together to create larger flocs to speed up the sedimentation process. Electrostatic repulsive forces, which prevent negatively charged particles from collecting on the substance, pose a challenge to this process. As a result, it takes longer to settle. To fix this issue, the particles have to be destabilized with a coagulant (El-taweel *et al.*, 2023). Therefore, coagulation happens when coagulants are added during relatively intense mixing to destabilize naturally occurring particles and macromolecules *(*Al-Risheq *et al.*, 2021).

The process of coagulation alone does not significantly help, it needs the process of flocculation to perform effectively (Mohd-Salleh *et al.*, 2019). Therefore, flocculation which allows slow mixing is a crucial step in water treatment to achieve optimum performance. The purpose of the flocculation stage is to detect the collision and enhance the aggregation of the particles as a result (El-taweel *et al.*, 2023).

2.1. Mechanisms of coagulation

In general, the coagulation process consists of four steps that are grouped according to the primary mechanism that causes aggregates to develop. These four steps include double-layer compression, charge neutralization, the formation of electrostatic patches, and the formation of inter-particle bridges (Ghernaout *et al.*, 2020; Mortadi *et al.*, 2017; Bordi *et al.*, 2004). Furthermore, flocculation takes place as a result of two basic phenomena, namely; orthokinetic which is a result of fluid motion, and peri kinetic which is caused by Brownian motion (Beljon, 2021). Fig. 1 shows the overall process of coagulation-flocculation in water treatment. The mechanisms for the coagulation process are described in the following subsections.

2.1.1. Charge neutralization

The colloidal particle's surface, which is typically negatively charged, is coated by an oppositely charged coagulant as part of the charge neutralization mechanism, which lowers and neutralizes the colloidal particle and brings the zeta potential down to almost zero net charge (Choy *et al.*, 2015). Reduced zeta potential, which arises from reducing and neutralizing the surface charge, aids in lowering or removing the energy barrier. As a result, colloidal particles are destabilized and begin to gather together and settle down (Alnawajha *et al.*, 2022).

2.1.2. Formation of inter-particle bridges

When long-chain polymers or polyelectrolytes stretch into a solution and form threads or fibers, they bridge the gap between numerous colloidal particles. A crucial component of bridging flocculation is the molecular weight of polymeric flocculants (Mohd-Salleh *et al*, 2019; Wei *et al.*, 2018). Polymers that possess a low degree of cationic charge and a high molecular weight should mainly work through the bridging mechanism since the polymers with large molecular weights have long-chained structures which significantly increase the number of vacant adsorption sites. (Alnawajha *et al.*, 2022).

2.1.3. The formation of electrostatic patches

Charged polymers or colloids bind to an oppositely charged particle in this process. Through areas of opposite charges, particles are drawn to one another, thereby coagulating the suspension (Agunbiade *et al.*, 2016). For the charge neutralization procedure, a patch-wise medium which is referred to as an electrostatic patch mechanism is used. The surface of the colloids will patch with different cationic species, resulting in particle surfaces with positive and negative charges. Surfaces of colloids with mixed charges will have fewer repelling forces and more van der Waals forces between the particles (Chong *et al.*, 2021).

2.1.4. Double-layer compression

The negatively charged colloidal particles draw ions of opposite charge to form a dense layer adjacent to the particle which is known as the Stern layer. The Stern layer's repulsive force and the dynamic equilibrium between the excess positive ions drawn in by the negatively charged core colloids cause the diffuse layer to form. The double-layer is a term used to describe such two layers in the colloid particle interfacial region (Zhao, 2020). The double-layer will be squeezed as soon as a coagulant (positively charged) is added to a colloidal solution due to electrostatic interaction between the ions and colloids. Double-layer compression is a crucial destabilizing mechanism in naturally occurring aquatic systems, even though it does not control the colloid destabilization process in water treatment (Ghernaout *et al.*, 2020).

3. Classification of coagulants

Different types of coagulants can be used for treating water (Tetteh *et al.*, 2017). These coagulants can be chemical, non-chemical, synthetic, or natural coagulants. Each type of coagulant possesses its unique properties with some of the coagulants having ions that will be positively charged and these will entrap the negative charge of the organic matter in the water that causes turbidity (Tetteh & Rathilal, 2020). An overview of synthetic organic polymers, natural coagulants, and inorganic coagulants and coagulant aids is provided in this section.

3.1. Inorganic coagulants and coagulant aids

Conventional chemicals which are utilized for coagulation are mainly aluminum or iron-based salts. Metal-based coagulants are most widely utilized because of their advantages which include the fact that they are low-cost, widely available, and can achieve removal efficiencies as much as 98.8%, 99.7%, and 92.3 % for removal of turbidity, total suspended solids and COD respectively (Al-Wasify *et al.*, 2023; Kurniawan *et al.*, 2023). The use of these metal-based coagulants for the purification of water is not without drawbacks, though. They may change the pH of the water since they deplete alkalinity; thereby resulting in lime or soda ash being added to maintain the desired pH levels (Iwuozor, 2019). Additionally, the use of metal-based coagulants causes the production of large amounts of sludge as well as the presence of residue metals in the sludge (Freitas *et al.*, 2018; de Souza *et al.*, 2016). The benefits and drawbacks of some inorganic coagulants for water treatment are listed in Table 1.

The settling properties of flocs produced by coagulants are improved by coagulant aids. A coagulant aid that has previously been utilized is activated silica. Activated silica was utilized as a coagulant aid together with Poly Aluminium Chloride (PAC) for enhanced coagulation of raw water from Yellow River Water (YW) and South-to-North Water

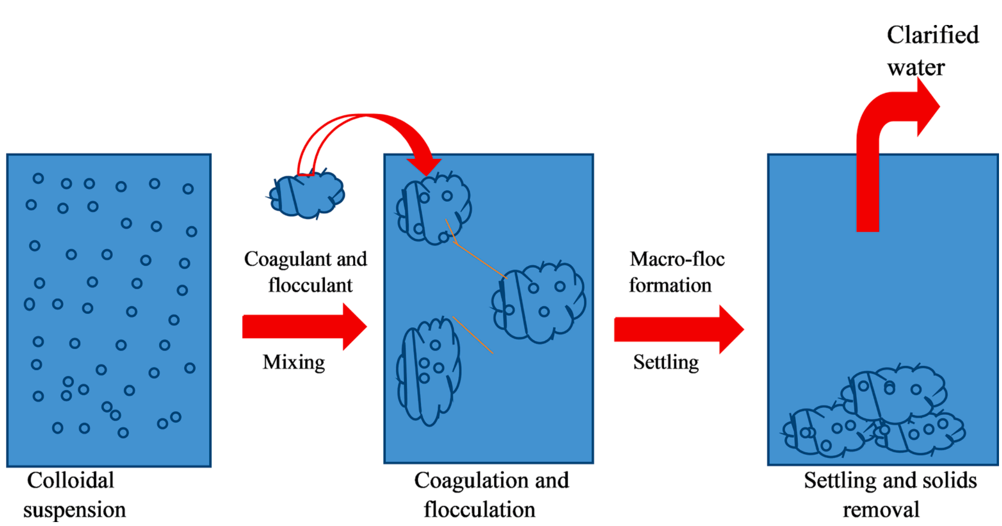

Fig. 1. Overview of the coagulation-flocculation process, adapted from Wilson (2014).

Table 1
Benefits and drawbacks of inorganic coagulants. Adapted from Thakur *et al.* (2021).

Coagulant	Benefits	Drawbacks	References
Aluminum sulfate (Alum) $Al_2(SO_4)_318H_2O$	• Low sludge volume index	• Limited pH effective range • Introduces dissolved aluminum salts residues to the water	Thakur *et al.*, 2021; Neukirchen & Ries, 2020; Zand and Hoveidi, 2015
Sodium aluminate $Na_2Al_2O_4$	• Efficient in hard waters • Mostly, low concentrations are needed.	• High cost • Ineffective for the treatment of soft water	Krupinska, 2020; Tripathy *et al.*, 2019
Polyaluminium chloride (PAC) $Al_{13}(OH)_{20}(SO)_4Cl_{15}$	• Rapid aggregation velocity • Bigger and heavier flocs than conventional Al(III) salts • Less dosage is required than conventional Al(III) salts • The pH of the treated water is unaffected.	• It has considerably lower molecular weight and size than organic polymers, and its stability to withstand subsequent hydrolysis is also significantly lower than for organic polymers flocculants	Abdo *et al.*, 2020; Gao *et al.*, 2002;
Ferric sulfate $Fe_2(SO_4)_3$	• Less sensitive to overdosage than aluminum-based coagulants	• Very caustic • It causes rust-colored stains that are visible and related to chemical spills and leaks. • Depletes alkalinity	Bahrodin *et al.*, 2021; Sadeghi *et al.*, 2017; Hassan, 2005
Ferric chloride $FeCl_36H_2O$	• Effective in a broad range of pH between 4 and 11	• Salts are added as dissolved solids to the water. • Doubles the amount of alkalinity that alum consumes	Bouchareb *et al.*, 2021; Bouchareb *et al.*, 2020
Ferrous sulfate $FeSO_47H_2O$	• It is less sensitive to pH than lime.	• Salts are added as dissolved solids to the water. • Normally, alkalinity must be added.	Marey, 2019
Lime $Ca(OH)_2$	• Does not add dissolved salts to the water	• pH-dependent • Produces vast quantities of sludge	Thakur *et al.*, 2021; Kumar *et al.*, 2017

Diversion (SNW) in Zhengzhou, China, with turbidity removal efficiencies of up to 96.5% obtained at PAC dosage of 35mg/L and activated silica dosage of 7 mg/L for source water YW and SNW blended in the ratio of 2:1 (Lu *et al.*, 2018). Other aids used at the time were sodium alginates and some soluble starch products which are still being utilized. Soluble starch products such as sago and tapioca were used for the removal of turbidity in river water achieving turbidity removal efficiencies of 93.7% at a dosage of 1000 mg/L and 96.4% at an optimum dosage of 2000 mg/L for tapioca and sago starch respectively (Zainol *et al.*, 2020). The fact that these compounds were well-known and had previously been employed in the food business gave them the benefit of being accepted as safe for water purification. Polyelectrolytes were later utilized and were more effective. They now consist of many synthetic products, particularly long-chain organic chemicals which can either be cationic, anionic, or non-ionic (Johnson & Elphinston, 2017).

3.2. Synthetic organic polymers

Synthetic organic polymers have been utilized for decades for the treatment of water and wastewater as flocculants and also as chemical aids for sludge dewatering (Heiderscheidt *et al.*, 2016). These high molecular weight polymers which are commonly referred to as polyelectrolytes are synthetic compounds that tend to strongly adsorb the particles on the surface in an aqueous suspension (Koshani *et al.*, 2020). Utilizing organic polymers in the process of treating drinking water can increase the settling rate, reduce costs and improve the water quality (Iwuozor, 2019).

Some of the advantages of using organic polymers are that they sometimes require lower dosages than metal salt coagulants and that they produce less sludge with better dewatering characteristics (Dayarathne *et al.*, 2021). It has been observed that floc re-growth after breakage caused by initial turbulent mixing is almost fully reversible with cationic polymers while mostly irreversible when metal salt coagulants are used (Zhu & Dou, 2021). Moreover, the introduction of organic coagulants does not consume alkalinity; therefore there will be no need for any pH adjustments of the treated water (Naceradska *et al.*, 2019). This was demonstrated by Sellami *et al.* (2014) in a study in which there was a slight change in pH from 4.94 to 4.56 when synthetic organic polymer polyacrylamide was used as a flocculant for the treatment of wastewater from the food industry. According to Bradney *et al.* (2019), there have been some concerns concerning the toxicity of synthetic polymers and their impacts on human health and also on the aquatic ecosystem which is a disadvantage of using synthetic organic polymers for water treatment. However, the toxicity of these products has mostly been linked to residual concentrations of non-reacted monomers and other contaminants which might be present in the treated water and are strictly limited by legislation worldwide (Heiderscheidt *et al.*, 2016).

3.3. Natural polymers

Natural polymers are readily available and environmentally friendly hydrophilic compounds that are also non-toxic to people (Tetteh & Rathilal, 2020). Many naturally occurring polymers possess intrinsic cationic properties which can be modified to give a cationic polyelectrolyte to be used for solid-liquid separations as flocculants (Sillanpää *et al.*, 2018). Examples of natural polymers are chitosan, starch, and cellulose derivates such as carboxymethyl cellulose (CMC), methylcellulose (MC), and chitin (Benabid & Zouai, 2016). Like most natural polymers, chitosan is non-toxic, making it generally accepted on a health basis (Dibyangana *et al.*, 2015).

Plants are a primary source of natural polymers. Examples of plant coagulants are Nirmali seeds, *Moringa oleifera* seeds, *Strychnos potatorum* seeds, *Jatropha curcas* seeds, *Cicer arietinum*, and Cactus (Nisa & Kishor, 2021; Patchaiyappan & Devipriya, 2021). The main merits of utilizing natural plant-based coagulants as point-of-use water treatment mechanisms are that they are cost-effective, unlikely to produce treated water that has extreme pH(outside the WHO recommended range of 6.5 to 8.5) and are highly biodegradable (Patchaiyappan *et al.*, 2020). These benefits are particularly enhanced if the plant from which the coagulant is produced is naturally located nearby in a rural area.

Natural coagulants have the disadvantage of being unable to handle huge pH variations. Most coagulants work effectively within a specified pH range, but their efficacy is greatly affected outside of this range (Gautam & Saini, 2020). Another disadvantage of employing natural coagulants is that they sometimes require higher dosages than synthetic coagulants (Aliyu *et al.*, 2015). The application of natural coagulants such as *Moringa oleifera* seeds in water treatment contributes to the surge of organic matter in treated water. This increase of organic matter in treated water is a disadvantage of using *Moringa oleifera* seeds in water treatment because organic matter contributes to the development of carcinogenic trihalomethanes when water is disinfected using chlorine (Camacho *et al.*, 2017).

4. Characterization of natural plant extracts according to the removal of key contaminants

The findings of investigations on the removal of turbidity, pathogens, and heavy metals from the water will be presented in this section.

4.1. Turbidity

To lower the turbidity of synthetic water using a standard jar test apparatus, Asrafuzzaman *et al.* (2011) evaluated the seeds of *Moringa oleifera, Cicer arietinum*, and *Dolichos lablab* for usage as locally accessible natural coagulants in Bangladesh. After introducing water-soluble extracts to the water, turbidity removal efficiencies obtained were 94.1%, 95.89%, and 88.9%, respectively. Seeds of *Cicer arietinum* treated the water to a final turbidity of 3.9 NTU which met WHO standards for turbidity in water as it was less than 5NTU whilst seeds of *Moringa oleifera* and *Dolichos lablab* achieved a final turbidity of 5.9 and 11.1 NTU and thus did not meet WHO standards for turbidity in drinking water. The natural coagulants in the study worked better with high turbidity water (90–120 NTU) in comparison to medium (40–50 NTU) or low turbidity water (25–35 NTU). These classifications of turbidity are according to Asrafuzzaman *et al.*, (2011) and may differ from one study to another. Fig. 2 shows the seeds of *Moringa oleifera, Cicer arietinum,* and *Dolichos lablab* which can be utilized in water treatment.

The turbidity reduction efficiencies obtained by Asrafuzzaman *et al.* (2011) were higher than those obtained in another study which was done in Malaysia using *Azadirachta indica, Stenochlaena palustris, Dicranopteris linearis, Syzygium polyanthum, Manihot esculenta, Piper sarmentosum, and Melastoma malabathricum*. The optimum dosage for *Piper sarmentosum* and *Manihot esculenta* was 5 g/L, which removed 24.2% and 22.2% of the turbidity, respectively (Ahmad *et al.*, 2022). *Azadirachta indica* removed 26.9% of the turbidity at 10 g/L, followed by *Stenochlaena palustris*, 24.9%, *Syzygium polyanthum*, and 17.5% of *Dicranopteris linearis. Melastoma malabathricum* finally achieved the removal of 12.2% with a dosage of 0.1 g/L, with the final turbidities ranging from 353.0 NTU to 412.5 NTU from an initial of 500± 50 NTU (Ahmad *et al.*, 2022).

The results obtained by Asrafuzzaman *et al.* (2011) are comparable to the turbidity removal efficiency used when calcium alginate was utilized as a natural coagulant to treat synthetic turbid water in a study by Saranya *et al.* (2022). The coagulation-flocculation process produced turbidity values of less than 5 NTU, which are acceptable for drinking water while utilizing alginate concentrations of 6–10 mg/L and calcium concentrations larger than 50 mg/L. A turbidity removal of greater than 93% was achieved and maximum removal of 99.3% was obtained (Saranya *et al.*, 2022).

Another study by Ali et al. (2010) produced similar results to what Asrafuzzaman *et al.*, (2011) obtained in their study. *Moringa oleifera* was used as a natural coagulant by Ali et al. (2010) to treat synthetic turbid water in a study carried out in Malaysia. A dosage of 0.4 mg/L resulted in final turbidity of 1.28 to 1.36 NTU, which is under the advised WHO guideline value of 5 NTU, and a turbidity removal effectiveness of 96.23%.

4.2. Pathogens

In a study conducted by Amran *et al.* (2021), *Carica papaya* seeds were used in Malaysia at a dosage of 196 mg/L and a pH of 4 to treat river water. Removal efficiencies of 57.6% and 62.1% were achieved for total coliform and *Escherichia coli* respectively. However, higher removal efficiencies of total coliform (99.61%) and *Escherichia coli* (99.74%) when *Moringa oleifera* seeds with a dosage of 600 mg/L were used to treat domestic wastewater in Brazil (Andrade *et al.*, 2021). In a separate study, *Magnifera indica* seeds with a dosage of 0.5 g/L were also used to remove 100% of both total coliform and fecal coliform in stream water (Okunlola *et al.*, 2020).

Asrafuzzaman *et al.* (2011) also carried out a study in which they used seeds from the plants *Moringa oleifera, Cicer arietinum*, and *Dolichos lablab* to successfully reduce the total coliform in turbid water by 89–96%. Total coliform in water was reduced by *Moringa oleifera* seeds from 1.35×10^3 cfu/100mL to 5.4×10^1 cfu /100mL. Additionally, the total coliform was reduced to 1.0×10^2 cfu/100mL and 1.1×10^2 cfu/100mL by *Cicer arietinum* and *Dolichos lablab*, respectively from 1.05×10^3 cfu/100mL. The water samples which were treated using the three natural coagulants did not meet the WHO drinking water quality standards of 0 cfu/100mL for total coliform in water and will therefore require further disinfection. Furthermore, a study by Ramavandi (2014) which was conducted in Iran also showed that fecal streptococcus was removed to almost 0 cfu/100mL from turbid water using a coagulant extracted from *Plantago ovata*. However, the fecal coliform was not reduced to 0 cfu/100mL and did not meet WHO drinking water quality standards.

Tubers of *Maerua subcordata* and seeds of *Moringa stenopetala,* which are shown in Fig. 3 below were used in a study in which coagulation and microbial reduction experiments were done on surface river waters in Ethiopia (Megersa *et al.*, 2016). Both plants displayed excellent performances in the reduction of microbial load (total coliform, *Escherichia coli,* and heterotrophic bacteria). The five rivers that were sampled contained *Escherichia coli* in the range of 153 to 166 cfu/100mL. After being treated with the natural coagulants, four of these water samples had 0 cfu/100mL, which complies with World Health Organization (WHO) drinking water quality requirements. However, one sample did not meet the WHO water quality standards as the final *Escherichia coli* load after treatment with *Maerua subcordata* and *Moringa stenopetala* was 2 and 1 cfu/100mL, respectively. Therefore, in this case, residual disinfection is very important to obtain zero colony-forming units in treated water (Pritchard *et al.*, 2009). A greater percentage of total coliform removal (100%) was noticed for the lowest turbidity value of 20 NTU than (98.4%) for the highest turbidity level of 195 NTU which was used in the study by Megersa *et al.* (2016). This higher percentage of microbial load removal in lower turbidity water than in higher turbidity water may be due to the increase in particles suspended in the

(a) *(b)* *(c)*

Fig. 2. Seeds of Moringa oleifera (a) (Paisley Farm & Crafts, 2022), Cicer arietinum (b) (Sergeev, 2015) and Dolichos lablab (c) (Exporters India, 2022).

(a) (b) (c)

Fig. 3. Seeds of Moringa stenopetala (a) (Moringa Matters, 2022), Plantago ovata (b) (Botany Today, 2018) and tubers of Maerua subcordata (c) (Gerald and Buff, 2002).

high-turbidity water that protects the bacteria from the action of the natural coagulants (Megersa *et al.*, 2016). Sharma & Bhattacharya (2017) suggest that the presence of clay, silts or sand, or organic, algae, and leaf particles causes turbidity which may shield bacteria, thus preventing disinfection chemicals such as chlorine from invading and destroying cells.

The antimicrobial effect of plant coagulants may be accredited to both flocculation (Nwaiwu & Lingmu, 2011) and bactericidal action (Oluduro *et al.*, 2010). The presence of alkaloids and tannins in plant species could contribute to antimicrobial activities (Shojaemehr *et al.*, 2020). Bacterial re-growth was raised as a huge issue of concern with natural coagulants and can be made better by purification of the active agent (Ahizi *et al.*, 2023).

4.3. Heavy metals

The seed cake of *Moringa oleifera* acts as a natural adsorbent for removing heavy metals from water samples (Ndibewu *et al.*, 2011). In a study which was done in Fiji, 60% of cadmium was eliminated by using *Moringa oleifera* seed cake (Nand *et al.*, 2012). This result concurs with the findings of Meneghel *et al.* (2013) in which 57.21% of cadmium was removed using *Moringa oleifera* seeds as a biosorbent in a study conducted in Brazil.

However, in a study done in Malaysia by Shan *et al.* (2017), more than 90% of cadmium was removed from the water samples collected from "The Sungai baluk" river when the seeds of *Moringa oleifera* were used as a natural coagulant for removal of heavy metals. The initial concentrations of heavy metals which included copper (1.401 mg/L), cadmium (1.887 mg/L), iron (1.414 mg/L), and lead (1.854 mg/L) were high. Results from this study as shown in Table 2 indicate that increasing *Moringa oleifera* seed cake concentration resulted in high removal efficiency of heavy metals from the "Sungai baluk" river samples. (Shan *et al.*, 2017).

In a study done in Malawi by Sajidu *et al.* (2005), 92.14% of iron was removed from synthetic contaminated water using *Moringa oleifera* seeds. This result is comparable with what was concluded in another study carried out by Shan *et al.* (2017), in which iron was reduced to zero in the water samples treated with *Moringa oleifera* seed cake. Moreover, the iron removal efficiency (92.14%) obtained in the study by Sajidu *et al.* (2005) is almost the same as the result obtained in Finland in the study by Righetto *et al.* (2021) in which 92.00% of iron was removed in landfill leachate using a tannin based product named HTH.

The percentage removal of lead using *Moringa oleifera* seeds in synthetic contaminated water was 89% in a study which was done by Sajidu *et al.* (2005) and 80% in ground and surface water in the study done by Subramanium *et al.* (2011). These values differed from that of 71% which was obtained by Shan *et al.* (2017) when *Moringa oleifera* seeds were used to treat water from "Sungai baluk'' river water. Concerning the level of lead in the treated water, the result which was obtained by Shan *et al.* (2017), did not meet the drinking water standards of WHO (2006). The level of lead was lowered to 0.537 mg/L. This amount of lead was above the allowable limit, which is less than 0.05 mg/L.

Table 2
Removal of heavy metals in water using natural coagulants.

Natural coagulant	Metal removed	Final Concentration (mg/L)	Level of removal (%)	WHO standards(mg/L)	Complied with WHO standards	Reference
Neem wood powder	Copper	0.5	95	2	Yes	Arshad & Imran, 2020
	Zinc	0.4	96	3-5	Yes	
	Manganese	0.6	94	<0.1	No	
	Lead	2.8	72	0.01	No	
	Chromium	2.5	75	0.05	No	
	Arsenic	0.75	25	0.01	No	
Pine Cone powder	Copper	0.1	99	2	Yes	
	Zinc	0.3	97	3-5	Yes	
	Manganese	0.4	96	<0.1	No	
	Lead	1.2	88	0.01	No	
	Chromium	1.4	86	0.05	No	
	Arsenic	0.75	25	0.01	No	
Carica papaya leaf powder	Lead	10.2	89.8	0.01	No	Seetha *et al.*, 2012
Opuntia ficus indica	Chromium	3.34	66.6	0.05	No	Mane *et al.*, 2011
	Nickel	1.16	88.4	0.02	No	
Moringa oleifera	Copper	0.001	99.9	2.00	Yes	Shan *et al.*, 2017
	Cadmium	0.029	98.5	0.003	No	
	Iron	0	100.0	No health-based guideline	Yes	
	Lead	0.537	71.0	0.01	No	
Dolichos lablab	Iron	<0.05	97.17	No health-based guideline	Yes	Kabir, *et al.*, 2019

In a study which was conducted in Fiji, Tonga, and Kiribati by Subramanium *et al.* (2011), *Moringa oleifera* seed cake was able to remove up to 90.00% of copper in water. This percentage removal is lesser than the one obtained in the study done by Shan *et al.* (2017), in which more than 99.90% of copper was removed from a water sample using *Moringa oleifera* seed cake. However, the copper removal efficiency of 90.00% obtained by Subramanium *et al.* (2011) is slightly greater than the copper removal efficiency of 87.02% which was obtained in a study by Skotta *et al.* (2023) in which *Lepidium sativum* seeds were used for removing copper in laboratory synthetic samples.

Copper, zinc, and iron were treated to meet WHO water quality standards among the heavy metals examined in this section, but manganese, chromium, lead, arsenic, and cadmium did not after treatment with various natural coagulants like neem wood, pine cones, and *Moringa oleifera* seeds. Manganese, chromium, lead, arsenic, and cadmium would therefore require additional treatment to comply with WHO water quality standards.

5. Criteria for analysis of natural coagulants

Natural coagulants that are derived from plants were analyzed by using environmental and technical criteria which include dosage, active ingredients, extraction method, sludge produced, toxicity, technical complexity, availability, environmental impact, and costs as suggested by Omran *et al.* (2021).

5.1. Dosage

In a study by Rayudu *et al.* (2022), dragon fruit foliage was employed as a natural coagulant to remove turbidity. The turbid water was prepared in the laboratory with an initial turbidity of 55 NTU. The optimum coagulant dosage was found to be 250 mg/L with final turbidity of 9 NTU and will therefore require further treatment to achieve the desired WHO standard of 5 NTU in drinking water (WHO, 2017). The results from the study by Sciban *et al.* (2005) showed that seeds of common bean *Phaseolus vulgaris* and indigobush *Amorpha fruticosa* at a dose of 5 mg/L were best used for treating water with a turbidity of 17.5 NTU, which was the lowest turbidity in the study. The extracts of the seeds of black locust *Robinia pseudoacacia* had good coagulation activity (greater than 50%) in water with a turbidity of 70 NTU in a dose of 30 mg/L and for lesser turbidity, lower dosages have a better performance. The optimum coagulant dosage obtained by Taiwo *et al.* (2020) when treating water with turbidity less than 50 NTU using *Moringa oleifera* seeds was 60 mg/L. The turbidity of the water dropped significantly ($p<0.05$) at this dosage, from 41.19 ± 1.5 NTU to 23.51 ± 1.03 NTU.

Seven plant species that are native to Malaysia were investigated for their potential to treat the turbidity of water. The plants are *Azadirachta indica, Stenochlaena palustris, Dicranopteris linearis, Syzygium polyanthum, Manihot esculenta, Piper sarmentosum, and Melastoma malabathricum* (Ahmad *et al.*, 2022). The optimum coagulant dosage for *Melastoma malabathricum* was 0.1g/L with turbidity removal of 12.2%. As for *Azadirachta indica, Stenochlaena palustris, Syzygium polyanthum,* and *Dicranopteris linearis,* the optimum coagulant dose was 10 000 mg/L with the removal efficiency being 26.9%; 24.9%; 24.9% and 17.5% respectively. *Piper sarmentosum* and *Manihot esculenta* achieved optimum coagulant dosages of 5000 mg/L with removal efficiencies of 24.2% and 22.0% respectively. The low turbidity removal efficiencies are due to the fact that the water extraction method was used therefore the ingredients which are responsible for coagulation were not adequately extracted (Ahmad *et al.*, 2022).

Moringa oleifera leaves extracts were used in a study by Pandey *et al.* (2020) for the removal of turbidity, fluoride, and *E.coli* in water. The initial values of turbidity, fluoride, and *E. coli* in water were 15.6 NTU, 2.3 mg/L, and 315 cfu/100mL respectively. After treatment at a dosage of 150 mg/L, *Moringa oleifera* leaves reduced the turbidity, fluoride, and *E. coli* to 6.1 NTU, 1.1 mg/L, and 41 cfu/100mL respectively. Turbidity and *Escherichia coli* did not meet WHO standards of 5 NTU and 0 cfu/100mL respectively whilst fluoride met the standard of 1.5 mg/L fluorides in drinking water (WHO, 2017).

5.2. Active ingredients

The active ingredients of *Moringa oleifera* seeds are soluble cationic proteins with a molecular weight of about 13 kDa and isoelectric pH values of 10 and 11(Ndabigengesere *et al.*, 1995). Legumes store proteins in seed organelles to provide nutrition for seed growth and development (Duranti & Gius, 1997). These proteins, including albumins, globulins (soluble in dilute salt solutions), prolamins (soluble in alcohol/water mixtures), and glutens (soluble in dilute acid or alkali), are categorized as storage proteins based on their solubility characteristics (*Shewry et al*, 1995). Globulins, such as arachin and coarachin in peanut (*Arachis hypogaea*) seeds, are the predominant proteins in legumes and play a crucial role when used as natural coagulants (Kristianto, 2017). *Moringa oleifera* seeds, known for their coagulation activity, contain a water-soluble protein called lectin (Ferreira *et al.*, 2011). The active ingredients in *Moringa oleifera* seeds are reported to be stable dimeric proteins that are completely soluble in water (Sapana *et al.*, 2012). Water-soluble proteins, ranging from 18.6% to 37.2%, are the main components found in *Moringa oleifera* seeds after lipids (Kumar *et al.*, 2022; Kristianto, 2017; Ferreira *et al.*, 2011; Duranti and Gius, 1997; Shewry *et al.*, 1995).

In a study conducted by Hussain *et al.* (2019), pine cone extract was investigated as a natural coagulant for purifying turbid water. The study found that pine cone extracts contain both cationic and anionic coagulating components. The anionic components are responsible for reducing turbidity at lower pH levels, while the cationic protein components are activated at higher pH levels. Other studies have shown that rice hull ash, which is rich in silica, can be used as a coagulant aid to enhance the effectiveness of aluminum or iron coagulants by forming larger and denser flocs(Adams & Mulaba-Bafubiandi, 2014; Abo-El-Enein *et al.*, 2011). Additionally, starch can be utilized as a natural coagulant due to its properties as a low-cationic polyelectrolyte (Oladoja, 2015). Table 3 shows the active ingredients from various coagulants which are responsible for the coagulation process.

Banana pith powder has been successfully used as a natural coagulant for treating river water, effectively removing turbidity, suspended solids, and some heavy metals (Kakoi *et al.*, 2016). The functional groups present in the banana pith, such as hydroxyl, carboxylic and ketone, aldehyde, and lactone groups, contribute to its coagulation capabilities. Inulin, found in banana pith juice, acts as an active coagulant agent by forming bridges of flocs, particularly in the treatment of spent coolant wastewater (Alwi *et al.*, 2013). Papaya seeds are known for their antimicrobial properties due to their various phytochemical contents (Peter *et al.*, 2014). Additionally, approximately 10% of papaya seed protein belongs to the albumin type, which can also serve as a coagulant agent (Kristianto, 2017). According to Jones & Bridgeman (2016), when Okra seed is used as a coagulant, it relies on proteins for turbidity removal. White mustard seed proteins have recently been employed to remove anionic dye direct black 19 from textile wastewater, achieving removal efficiencies of up to 90.9% (Tie *et al.*, 2019).

The active ingredients for most natural coagulants which have been studied for water treatment in several studies are mainly proteins (Choudhary & Neogi, 2017; Kristianto, 2017; Ramavandi, 2014; Ferreira *et al.*, 2011; Ndabigengesere *et al.*, 1995).

5.3. Extraction method

Okuda *et al.* (1999) developed a method for extracting the active ingredient for coagulation from *Moringa oleifera* seeds using a solution of sodium chloride and other salts. This method showed better coagulation activity for removing kaolinite turbidity compared to the conventional water extraction method. The salt extraction method achieved over 95%

Table 3
Active ingredients from various coagulants responsible for coagulation in water treatment.

Coagulant	Active ingredient	Coagulation mechanism	References
Moringa oleifera	• Cationic proteins • Water-soluble proteins • Protein lectin	• Charge neutralization and adsorption of the colloidal particles	Choudhary and Neogi, 2017 Ferreira *et al.*, 2011 Ndabigengesere *et al.*, 1995
Nirmali	• Anionic polyelectrolytes	• Interparticle bridging	Sanghi *et al.*, 2002
Rice husk ash	• Silica	• Enmeshment in a precipitate	Adams and Mulaba-Bafubiandi, 2014 Abo-El-Enein *et al.*, 2011
Papaya seed	• Protein- albumin type	• Electrostatic interactions	Melinda *et al.*, 2022 Kristianto, 2017
Banana pith powder; banana pith juice	• O-H and C-H groups • The carboxylic (COO-double bond) and asymmetrical ionic carboxylic (-COOH) groups, • Other function groups such as the C-O group of ketones, aldehydes, and lactones, • C-O-C and O-H groups of polysaccharides and the C-N groups • Inulin	• Charge neutralization combined with low bridging	Kakoi *et al.*, 2016 Alwi *et al.*, 2013
Okra seed	• Okra seed protein	• Charge neutralization	Jones & Bridgeman, 2016
Mustard seed	• Mustard seed protein	• Adsorption and charge neutralization	Tie *et al.*, 2019

Table 4
Extraction methods used when utilizing natural coagulants for water treatment.

Coagulant	Extraction method	References
Moringa oleifera seeds	• Salt (NaCl, KNO_3, KCl, $NaNO_3$) • Water • Hexane • Acetone • Ethanol	Bouchareb *et al.*, 2021 Okuda *et al.*, 1999 Camacho *et al.*, 2017 García-Fayos *et al.*, 2016
Peanut seeds	• Water • Salt (NaCl, KNO_3, KCl, NH_4Cl and $NaNO_3$)	Birima *et al.*, 2013
	• Salt (NaCl) • Water	Birima *et al.*, 2015
Plantago ovata seeds	• Salt ($FeCl_3$)	Ramavandi *et al.*, 2015 Ramavandi, 2014
	• Water • Salt (NaCl) • Ammonium acetate	Dhivya *et al.*, 2017
Opuntia ficus-indica	• Ultrasound-assisted extraction (UAE) • Water	Adjeroud- Abdellatif *et al.*, 2020 Gomes *et al.*, 2016
Pine cone	• Water	Hussain *et al.*, 2019

coagulation of the initial 50 NTU kaolin turbidity using a significantly lower dose (4 mL/L) compared to the water extraction method, which required 32 mL of coagulant to remove about 78% of the same turbidity. The improved efficiency of coagulation with sodium chloride is attributed to its salting-in mechanism, increasing protein solubility as the salt's ionic strength rises. Another study by Bouchareb *et al.* (2021) found that salt extraction with sodium chloride resulted in a higher amount of dissolved coagulant agent compared to water extraction.

In a study by Birima *et al.* (2015), a de-oiled extract from peanut seeds was utilized for treating palm oil mill effluent. The active coagulation component was extracted using three different concentrations of sodium chloride: 0 mol/L (distilled water), 1 mol/L, and 2 mol/L. The highest removal of total suspended solids (TSS) and chemical oxygen demand (COD) was achieved with the 2 mol/L sodium chloride extract, resulting in 94.7% and 73.5% removal, respectively. In comparison, using distilled water for extraction yielded lower removal efficiencies of 90% for TSS and 66% for COD. Table 4 shows different extraction methods which are utilized when using natural coagulants for water treatment.

In a study by Ramavandi *et al.* (2015), salt extraction using ferric chloride was used for the extraction of proteins from the seeds of *Plantago ovata*. Adjeroud-Abdellatif *et al.* (2020) made use of ultrasound-assisted extraction to extract proteins from the natural coagulant *Opuntia ficus-indica* by subjecting the coagulant to ultrasound waves by a sonicator probe.

Many methods have been used to extract active ingredients from natural coagulants. These include water and salt extraction, ultrasound-assisted extraction, and extraction using hexane, acetone, and ethanol. The most common extraction methods in several studies include water and salt extraction (Bouchareb *et al.*, 2021; Hussain *et al.*, 2019; Birima *et al.*, 2015; Ramavandi *et al.*, 2015; Okuda *et al.*, 1999). Salt extraction method produced better results than water extraction methods in several studies in which both of the methods were used (Behera & Balasubramanian, 2019; Benalia *et al.*, 2018; Birima *et al.*, 2015; Vishali & Karthikeyan, 2015; Okuda *et al.*, 1999) .

5.4. Sludge produced and how safe it is for reuse

Ndabigengesere *et al.* (1995) conducted a study to compare the effectiveness of *Moringa oleifera* seeds and alum as coagulants in water treatment. At a dosage of 500 mg/L, the volume ratio of sludge produced by alum, shelled *Moringa oleifera* seeds, and non-shelled *Moringa oleifera* seeds was 5:2.5:1 respectively. The type and amount of coagulated materials influenced the sludge generated when using *Moringa oleifera* seeds. However, the advantage of using *Moringa oleifera* seeds is that all the by-products are organic and biodegradable. Additionally, the sludge produced by *Moringa oleifera* coagulation is non-toxic and significantly smaller in volume compared to the chemical sludge produced by alum coagulation, which contains aluminum hydroxide precipitates. The differences in sludge volume can be attributed to the sweep coagulation process. In the case of *Moringa oleifera*, the sludge is mainly dependent on the dosage and suspended particles (Vega *et al.*, 2021).

In another study, the efficiency of two natural coagulants, namely calcium lactate and tannic acid was assessed and compared to conventional coagulants; namely, polyaluminium chloride and ferric chloride (Kaji *et al.*, 2020). An initial turbidity of 900 NTU was used to test the four coagulants to compare the sludge produced. After 30 minutes, it was observed that the two natural coagulants created less deposited sludge than the other two chemical coagulants. It was therefore noted that the utilization of natural coagulants results in less sludge produced which is also biodegradable.

5.5. Toxicity

Toxicity is an important factor in evaluating natural coagulants. Genotoxicity refers to the damaging impact on the genetic material of a cell, potentially leading to cancer, mutations, or birth defects (Cinthura *et al.*, 2017). Cytotoxicity, another type of toxicity, refers to the harmful effects on cells caused by toxic agents, which may ultimately result in cell death. (Salih *et al.*, 2019). Studying the cytotoxic, genotoxic, and mutagenic effects of plant compounds can help minimize the potential health risks associated with these substances

According to Igbokwe *et al.* (2018), an acute toxicity test demonstrated that *Moringa oleifera* seeds are safe for consumption, with an LD50 value of 14 g/kg. Rolim *et al.* (2011) conducted a study on the genotoxicity of an aqueous seed extract of *Moringa oleifera*, using various assay systems. The results indicated that the seed extract was not genotoxic and did not pose a health risk. Araújo *et al.* (2013) evaluated the cytotoxicity of an aqueous extract of *Moringa oleifera* seeds and found no signs of systemic toxicity or mortality in mice. Additionally, Arnoldsson *et al.* (2008) observed that *Moringa oleifera* seed cake is a non-toxic agent used for water treatment. Furthermore, chitosan, as highlighted by Aider (2010) is a natural, abundant, and non-toxic biodegradable linear copolymer.

Sanmugapriyaa & Venkataraman (2006) conducted acute and chronic toxicity studies on the aqueous extract and seed powder of *Strychnos potatorum Linn* seeds, commonly used for water treatment. The study involved Wistar albino mice and rats, and no toxic effects were observed in the animals even at a dose of 2,000 mg/kg administered orally. Similarly, Doppalapudi (2019) administered high doses (up to 2000 mg/kg) of seed extracts of *Cicer arietinum* to normal rats orally. No mortality was observed in the rats, indicating the absence of toxic effects from the seed extracts of *Cicer arietinum* even at high doses.

From the studies which were considered, it is evident that various natural coagulants such as *Moringa oleifera, Strychnos potatorum Linn*, and *Cicer arietinum* are non-toxic and can therefore be safely used for water treatment.

5.6. Technical complexity

Varkey (2020) described a household technique for reducing the turbidity of surface water from rivers. The method involved adding 0.25g of seed powder to 1 liter of water in a container and vigorously swirling it for 20 to 25 seconds. After allowing the water to settle for an hour, the clear supernatant was poured off and filtered using a fine mesh cotton cloth. According to Babu & Chaudhuri (2005), seeds of *Strychnos potatorum* and *Moringa oleifera* can be easily implemented at the household level, since the implementation procedure does not require extensive technical expertise.

An uncomplicated setup for treating water at the household level would be to dose 10 L of contaminated water with *Strychnos potatorum* seed or *Moringa oleifera* seed as a coagulant (2% suspension prepared with distilled water). This is then followed by mixing via hand-stirring for a period of 2 to 3 minutes and filtering the water directly via a sand filter. The sand filter can be composed of 1,200 mm long and 150 mm internal diameter PVC pipe packed up to a depth of 500 mm using fine river sand, with 20-30 mm of pea-sized gravel at the bottom and arrangement for acquiring an initial flow rate of 3 L/minute. About 2 or 3 filter runs can be done every day. The sand in the filter must then be removed, thoroughly cleaned with water, and put back in the filter when the rate of filtration has significantly decreased (Babu & Chaudhuri, 2005).

According to Price (2007), *Moringa oleifera* seeds can be easily utilized for household water treatment using a simple process that involves removing the wings from the dry seeds and grinding them into a powder. The powder is then mixed with water, agitated for approximately five minutes, and filtered through a piece of woven fabric after an hour, resulting in treated water. Another technique involves immersing a cloth with seed powder in water, typically overnight, to allow contaminants to coagulate. The purified water is then decanted, leaving the coagulated particles at the bottom, and the cloth holding the seeds is removed. Foidl *et al.* (2001) reported that this method can eliminate up to about 99% of colloidal material, with one seed per liter recommended for slightly polluted water and two seeds for heavily polluted water.

In a study conducted by Burgos-vergara *et al.* (2020) in Colombian villages, the use of *Moringa oleifera* and *Cassia Fistula* was explored. The seeds of both plants were peeled and ground separately using laboratory and special seed grinders. The resulting fine powders were stored in Ziploc bags to prevent moisture absorption. 10 g of each powder was added to 1 liter of raw filtered river water in two 2-liter plastic bottles. The bottles were vigorously shaken for 1 and 2 minutes respectively (fast mixing), followed by an additional 5 minutes of slower shaking. To ensure complete dissolution of the natural compounds, the water and coagulant were manually mixed using consistent top-to-bottom and bottom-to-top movements. The water was then left undisturbed for 2 hours to allow for sedimentation to occur.

In terms of the practical application of natural coagulants, the studies which were considered show that the coagulants require minimal technical expertise to implement and can therefore be easily implemented even in low-income communities.

5.7. Availability

Previous studies have demonstrated the availability and extraction of natural coagulants from a variety of sources, including waste biomass, natural products, and even microbes (Saleem & Bachmann, 2019; Lee & Chang, 2018; Kanmani *et al.*, 2017). Thus, it can be inferred that some naturally occurring coagulants have dependable and readily accessible sources. Since plants like *Moringa oleifera* only produce mature, dried seeds twice a year, maintaining a consistent supply of raw materials that meet the minimum quality requirement is an inconvenience when considering using natural coagulants for large-scale water treatment facilities (Saleem & Bachmann, 2019).

5.8. Environmental Impact

Water utilities may be interested in using biodegradable natural coagulants that can reduce sludge production while also not adding to the sludge's toxicity (Dorca *et al.*, 2018) .If the organic sludge produced by natural coagulants could be used for other tasks, such as wastewater treatment, in the construction industry for producing building materials such as cement, concrete, and mortar, for agricultural use as soil conditioners, and land-based uses, it might provide environmental sustainability (Ahmad *et al.*, 2016).

Rarely is the secondary waste produced by the chemical-based extraction, purification, or synthesis of natural coagulants highlighted. Natural coagulant residues are regarded as organic materials that may interact with disinfectants which would have been produced by a subsequent disinfection process to produce carcinogenic disinfection byproducts. Therefore, natural coagulants should be used cautiously if a downstream disinfection process is available (Ang & Mohammad, 2020).

5.9. Costs

According to cost estimates, the cost of obtaining the natural coagulant from *Moringa oleifera* seeds includes the cost of the raw materials, chemical compounds (n-hexane), the electrochemically activated solution, energy consumption, labor costs, and cost for storage of the substance (Hoa & Hue, 2018). Income can be gained from the sale of oil extracted from *Moringa oleifera* seeds and the fatty de-cake for reuse in composting. The unit prices of the natural coagulants alginate and chitosan are \$12/kg and \$19/kg (Saranya *et al*, 2014). In Ethiopia, *Moringa stenopetala* seeds are sold on the market and a kilo costs about 40 Ethiopian Birr (USD\$1.40) with the cost of treating water per m^3 using the same coagulant being USD\$0.042 (Megersa *et al*., 2019). On the other hand, the price for alum is about \$0.30- \$0.50/ kg (Saranya *et al*., 2014). The cost of treating water using alum differs, for instance, Keeley *et al.* (2012) state that it is USD\$0.05 per m^3, Phillip (2013) reports that it is USD\$1.50 per m^3 whilst Hamawand *et al.* (2017) state that it is USD \$0.10 per m^3.

In the study by Kaji *et al.* (2020) both natural coagulants (calcium lactate and tannic acid) had higher water treatment costs than chemical coagulants polyaluminium chloride and ferric chloride as shown in Table 5. The cost was calculated based on the coagulant optimum dosage and the cost per kilo of each of the coagulants for 1 m^3 of the treated water. According to Kangama *et al.* (2018), the estimated cost per m^3 of treating water using chitosan is USD\$0.025. Table 5 gives the costs associated with using different natural and chemical coagulants.

In the studies examined in this paper, the cost of water treatment using natural coagulants was found to be higher than that of chemical coagulants in certain cases. However, there were also instances where natural coagulants had lower water treatment costs. These findings indicate that, in certain situations, natural coagulants can be economically viable for large-scale use.

6. Coagulation performance of conventional chemical coagulants as compared to coagulants derived from plant extracts

In a comparative study by Gandiwa *et al.* (2020), the effectiveness of blending extracts of *Cactus Opuntia* pads and *Moringa oleifera* seeds with a chemical coagulant in raw water treatment was examined. The results showed that alum achieved the highest turbidity removal efficiency, reducing turbidity from 28.4 to 2.4 NTU (91.5% removal) at an optimum dosage of 45 mg/L. *Moringa oleifera* achieved a turbidity reduction of 88.7% to 3.2 NTU at a dosage of 50 mg/L, while *Cactus Opuntia* reduced turbidity by 89.4% to 3 NTU. All coagulants achieved turbidities below the WHO guidelines of 5 NTU(WHO, 2017).

Cactus Opuntia extracts were successful in removing turbidity from water through adsorption and interparticle bridging mechanisms (Gandiwa *et al.*, 2020; Nharingo *et al*, 2015). *Moringa oleifera* seed protein also exhibits coagulating properties based on adsorption (Nouhi *et al.*, 2019). In a study by Tsamo *et al.* (2021), alum demonstrated the highest turbidity removal efficiency in raw water and slaughterhouse wastewater (64.61%), surpassing rice husk, cypress leaves, and eucalyptus leaves with removal efficiencies of 58.53%, 54.16%, and 28.10%, respectively. However, in a study conducted by Elsayed *et al.* (2020), it was found that Fenugreek seed extracts achieved a high turbidity removal efficiency of 98% in synthetic turbid water, outperforming alum with a lower efficiency of 85%. The flocculation process using Fenugreek extract likely involved an adhesion mechanism, where the proteins adhered directly to the surface and bridged the kaolin particles, facilitating their flocculation (Elsayed *et al.*, 2020). On the other hand, the coagulation-flocculation process using rice husk was attributed to charge neutralization and particle bridging mechanisms (Huzir *et al.*, 2019).

In a comparative study conducted by Beyene *et al.* (2016), cactus powder, alum, and their combination were analyzed for their impact on various physiochemical parameters using the jar test. The study found that increasing the dosage of cactus powder from 1000 mg/L to 7000 mg/L resulted in a turbidity reduction ranging from 23.90% to 54.00%. Similarly, increasing the alum dosage from 1000 mg/L to 7000 mg/L led to a turbidity reduction ranging from 28.46% to 58.20%. The use of cactus powder had a minimal effect on the water's pH, with the final pH values remaining relatively unchanged, while alum caused a significant drop in pH to 4.18 (acidic) at a dosage of 7000 mg/L, compared to the initial pH of 7.81. The decrease in pH caused by alum usage in water treatment can deplete alkalinity, requiring additional measures and costs to maintain a neutral pH (Hashim *et al.*, 2013; Napacho & Manyele, 2010). In a study by Beyene *et al.* (2016), using cactus powder and alum as coagulants resulted in increased total dissolved solids (TDS), conductivity, and salinity of the water sample. Cactus powder increased these parameters by 93.8%, 68.7%, and 97.1%, respectively, while alum increased them by 167.8%, 68.7%, and 180.0%, respectively. This indicates that cactus powder performed relatively better in maintaining TDS, conductivity, and salinity. In another study using alginate as a natural coagulant (Saranya *et al*, 2022), negligible changes were observed in the pH and conductivity of the water sample.

In the study by Gandiwa *et al.* (2020), the initial pH of the untreated water was 7.05. With the introduction of alum at a dosage of 60 mg/L, the pH decreased to 5.00. When *Moringa oleifera* and *Cactus Opuntia* were used at the same dosage, they slightly reduced the pH to 6.4 and 6.5, respectively. These pH values obtained with *Cactus Opuntia* fell within the WHO's pH range of 6.5-8.5 for potable water(WHO, 2017).

Table 5
Costs for treating water using natural and chemical coagulants.

Coagulant	Cost of treating water using coagulant per m^3 (USD)	Source of raw water	Country of study	Reference
Calcium lactate	0.009	Zayandehrood River		
Tannic acid	0.004		Iran	Kaji *et al.*, 2020
Poly aluminium chloride	0.0017			
Ferric chloride	0.0024			
Synthesized inorganic polymeric coagulant-medium basicity	0.076	Bisalpur dam	India	Solanki *et al.*, 2022
Inorganic polymeric coagulant-ultrahigh basicity	0.076			
Calcium chloride	0.064	Laboratory-prepared turbid water samples	Turkey	Çoruh, 2005
Alum	0.008			
		Inlet point of Ankara Ivedik Drinking Water Treatment Plant		
Moringa stenopetala	0.042	Synthetic turbid water	Ethiopia	Megersa *et al.*, 2019
Chitosan	0.025	Raw water from the Han River	South Korea	Kangama *et al.*, 2018
Azadirachta indica A. Juss	0.56	Urban waste water	India	Thirugnanasambandham & Karri, 2021
Alum	1.73			

However, when *Moringa oleifera* was used, the final pH was slightly outside the recommended range. The conductivity of the water increased by 51% with a dose of 60 mg/L of alum. Similarly, the conductivity increased by 38% for *Moringa oleifera* and 36% for *Cactus Opuntia* when the dosage was increased from 0 to 60 mg/L. The increase in conductivity is attributed to the dissociation of the coagulant, generating ions that enhance electrical conductivity. *Moringa oleifera* and *Cactus Opuntia* have a lower dissociation capacity in water compared to alum, resulting in a lesser increase in conductivity for these coagulants (Marobhe *et al.*, 2007).

In a separate study in which both natural and chemical coagulants were used for the treatment of palm oil mill effluent, it was observed that alum had the greatest dose requirement of 4000 mg/L as the optimum whilst *Moringa oleifera* had 2000 mg/L, chitosan 400 mg/L and zeolite 1000 mg/L (Jagaba *et al.*, 2020). The study demonstrated that more alum coagulant was required to treat the sample water as compared to natural coagulants which include *Moringa oleifera*.

From the studies which were analyzed, it was observed that alum had generally higher turbidity removal efficiencies than natural coagulants such as cactus, rice husk, and eucalyptus leaves. However, treatment with some of the natural coagulants results in final turbidity which met WHO guidelines for drinking water quality. Natural coagulants were also generally better than alum in maintaining the physicochemical parameters of the water such as pH, TDS, conductivity, and salinity.

7. Potential for using natural plant extracts for water treatment

Various natural coagulants such as *Moringa oleifera, Cicer arietinum, Plantago Ovata, Maerua subcordata,* and *Carica papaya* have been investigated in various studies and have proved to be able to remove impurities such as chromium, nickel, cadmium, *Escherichia coli,* and turbidity (Saranya *et al.*, 2022; Arshad & Imran, 2020; Megersa *et al.*, 2016). The successes of these studies at lab scale call for further upscaling of use of these coagulants at water and waste water treatment plants. Moreover, an intriguing idea that might improve the coagulation process is the idea of multifunctionality. Coagulants that can remove both dissolved and undissolved pollutants can speed up the treatment process and provide several advantages, including cost savings and reduced environmental footprint. There is also potential to come up with hybrid coagulants by combining natural coagulants with other already existing coagulants to achieve favorable levels of removal efficiency for different contaminants. Furthermore, since these coagulants are obtained from natural sources, the coagulants can be easily accessed (Ang & Mohammad, 2020).

8. Constraints of using natural plant extracts for water treatment

Plant-based coagulants have to go through some processes before they can be utilized for treatment unlike conventional chemical coagulants which are readily available for purchase and use (Kurniawan *et al.*, 2020). The extraction of natural coagulants from plants depends on the characteristics of the plant in question but generally, the processes involve crushing, sieving, dialysis, washing, delipidation, removal of insoluble matter, filtration, and ion exchange (Ali et al., 2010; Okuda *et al.*, 2001). Therefore, this processing which is required every time they are used is a challenge since the conventional chemical coagulants which are being currently used are readily available to use. To make the utilization of bio coagulants/bio flocculants practical and accessible, it is necessary to simplify these complex extraction processes. Future research should focus on preserving the longevity of active chemicals and converting them into powdered form for easier handling and storage (Kurniawan *et al.*, 2020).Moreover, resources that are used as natural coagulant have to compete with other needs for which they have to be used such as basic foods.

Furthermore, the use of these resources as coagulants has to be sustainable to avoid encountering scarcity challenges in the long-term application (Kurniawan *et al.*, 2020). Therefore, considering the huge amounts of water being currently treated using conventional coagulants, it implies that a vast quantity of the plant extracts has to be exploited in the long-term application and this may not be sustainable in the long run. Plants like *Moringa oleifera* also require processing and storage, increasing expenses and making it difficult to, meet the demand for natural coagulants as a replacement for chemical coagulants (Saleem & Bachmann, 2019). However, to deal with the issue of vast quantities of plant extracts being exploited, large plantations of the plants can be developed such that the plants are produced on a commercial scale and continuously to ensure viability.

Furthermore, another constraint of using natural coagulants for water treatment is that in some cases, these natural coagulants have been proven to be good for high turbidity but limited efficiency has been attained for low turbidity water (Asrafuzzaman *et al.*, 2011). Another challenge which is being faced in the use of natural plant extracts as coagulants is the lack of industrial confidence to adopt natural coagulants for water treatment due to concerns about the cost-effectiveness and performance consistency of the coagulants for large-scale water treatment (Ang & Mohammad, 2020). In addition, most of the performance results of natural coagulants which have been reported have been limited to lab-scale studies and the move to real industrial applications has been hard to come by.

The potential of natural coagulants to perform well under real application challenges such as fluctuating feed water quality, steady supply of natural coagulants with consistent quality, and storage and handling of the coagulants has not yet been established. Natural coagulants are also vulnerable to degradation where the active compounds such as proteins and polysaccharides may age during storage or be altered because of microbial attacks and external environmental factors during extraction and purification of the coagulants (Abidin *et al.*, 2019; Ho *et al.*, 2014). This will create a problem for the long-term storage of natural coagulants as the degradation of active compounds will affect the coagulation efficiency. Consequently, this has critical impacts on the commercialization potential of natural coagulants. This is because the performance of the coagulants would have been affected due to transportation and storage problems for the coagulants (Ang & Mohammad, 2020). This can be addressed by coming up with ways to process the extracts and also adding preservatives which will ensure that the extracts can be stored for a long time without being altered or degraded.

9. Opportunities and drawbacks for commercialization of natural coagulants

The successful commercialization of natural coagulants relies on their ability to maintain treatment performance at a comparable or lower cost than traditional chemical coagulants. However, making direct comparisons of coagulant types, processing stages, and costs across different geographic regions is challenging due to factors such as currency rates, inflation, and cost value accuracies (Freitas *et al.*, 2018).

The commercialization of natural coagulants often faces obstacles due to financial dependence and investor scepticism toward new products. To enhance the development of natural coagulants, it is important to understand the associated risks and weaknesses. However, most published results are limited to laboratory-scale studies, which might not be sufficient for real-time applications (Bahrodin *et al.*, 2021). A breakthrough in this sector can be achieved by emphasizing the combination of natural and chemical coagulants. Approval from regional governing organizations is also necessary for successful commercialization, but the stringent screening and documentation requirements can make obtaining approval challenging. To incentivize water treatment operators to adopt natural coagulants, tax refunds, and subsidy programs could be introduced (Choy *et al.*, 2014).

There is also a need for synergies between the research institutions researching these natural coagulants with the industries and municipalities which treat water and wastewater so that pilot studies can be done to determine how the natural coagulants perform in a large-scale water or wastewater treatment plant and the operating conditions under which they work.

In addition, providing loans to individuals interested in cultivating plants like *Moringa oleifera* and *Elephantorrhiza goetzei* for natural coagulant production on large areas of land can be considered. The main challenge in implementing plant-based natural coagulants in terms of sustainability lies in the large-scale cultivation of plants to meet industrial demands. Initially, there may be increased industrial costs due to technological adjustments, the development of new tools and machinery, and the establishment of new professional requirements. However, over time, there will be a significant reduction in the process costs and associated pollutants. Moreover, this approach can contribute to job creation since extensive land cultivation will be required for growing these plants (Freitas *et al.*, 2018).

There is potential for these natural coagulants to be commercialized and made available on the market in the same way in which chemical coagulants are readily available on the market. For this potential to be realized, investigations should be done on how to process the natural coagulants so that they are used in powder form and also find ways to make sure that there is a constant supply of the natural coagulants on the market to ensure industrial confidence in the products.

10. Discussion

Various studies have demonstrated that plant-based extracts have been successful in the removal of contaminants such as heavy metals, turbidity, and pathogens in water (Hussain *et al.*, 2019; Shan *et al.*, 2017; Sharma & Bhattacharya, 2017; Megersa *et al.*, 2016;). Turbidity removal efficiencies higher than 90% can be achieved using natural coagulants (Saranya *et al.*, 2022; Asrafuzzaman *et al.*, 2011). However, there is a challenge of lower efficiencies with water of lower turbidity. In the study by Asrafuzzaman *et al.* (2011), the removal efficiency increased from 86.9% to 94.1% for water with 100 NTU as the coagulant dosage increased from 50 mg/L to 100 mg/L as compared to an increase of removal efficiency from 65.6% to 69.4% as the coagulant dosage increased from 50 mg/L to 100 mg/L for lower turbidity of 48 NTU. Therefore, there is a need for further study on how best water with low turbidity can be treated with natural coagulants. A possible solution would be to spike the water with kaolin clay to increase the raw water turbidity before the natural coagulant is introduced. Pathogens can also be successfully removed using natural coagulants such as *Plantago ovata,* where removal efficiencies of approximately 96.1%; 98.1%, and 98.3% were achieved for fecal coliforms, total coliforms, and fecal streptococcus respectively (Ramavandi, 2014).

To achieve the best pathogen removal results for some of the coagulants, the water has to be of low turbidity. In the study by Yimer and Dame (2021), salt crude extract of papaya seed achieved a higher total coliform removal (88.97%) at a lower initial turbidity of 94.20 NTU than the 87.65% removal efficiency achieved at a higher initial turbidity of 392.70 NTU. Moreover, Marobhe & Sabai (2021) achieved 51.3% removal of total coliforms at initial turbidity of 1000 NTU using *Moringa oleifera* seed whilst Vunain *et al.* (2019) obtained a higher microbial load (96.65%) at lower initial turbidity of 278 NTU using *Moringa oleifera* seed. Therefore, if the water has higher turbidity, it can be treated in two stages. For the first stage, the natural coagulant is first introduced to reduce turbidity, and further dosing of the coagulant is done in a separate stage where the natural extract will now be working as a disinfectant. Heavy metals can also be successfully removed in water (Arshad & Imran, 2020). Heavy metal removal of up to 89.80% has been obtained for dangerous heavy metals such as lead in water using natural coagulants such as *Carica papaya* leaves (Seetha *et al.*, 2012). Natural extracts can be used in conjunction with conventional methods of removing heavy metals in water such as the ion exchange process and adsorption-based separation. This approach is useful when natural coagulants cannot reduce the concentration of the heavy metals to acceptable WHO standards.

Natural coagulants can be analyzed based on the dosage required for optimum removal of contaminants to determine whether it will be viable to use the coagulant, especially on a large scale. The active ingredient in the coagulant is also another important aspect of analyzing natural coagulants. Different components within natural coagulants can be responsible for the coagulation process. These include proteins, silica, organic polyelectrolytes, and starch (Oladoja, 2015; Ramavandi, 2014; Sanghi *et al.*, 2002) . It is therefore important to be aware of the active ingredient responsible for coagulation as that information can be exploited to enhance the coagulation capabilities of the natural coagulant. The extraction method is also another critical component when analyzing natural coagulants. This is because different extraction methods such as water and salt extraction result in differing coagulation activity and this can be used to design multi-stage experiments *(*Bouchareb *et al.*, 2021). There are also several other factors to consider when analyzing natural coagulants. These include the nature of the biomass produced and determining whether it is safe to use as a soil enhancer based on its components and toxicity since any residual toxic substances will pose a danger to the health of humans and the environment at large. The practical application of natural coagulants in communities has to be relatively easy so that even people in marginalized areas can easily adopt the technology.

11. Conclusion

The information gathered in this study shows that plant-based extracts can potentially replace conventional chemical coagulants if the challenges which are associated with using the extracts are addressed. Various plant extracts from plants such as *Moringa oleifera, Cactus Opuntia, Maerua subcordata, Cicer Arietinum, Dolichos Lablab,* and pine cone have been successfully used to treat raw water samples. *Moringa oleifera* and *Cactus Opuntia* have reduced turbidity to less than 5 NTU which is the WHO standard for turbidity in drinking water. Various natural coagulants have also been used to remove *Escherichia coli,* total coliform, and heavy metals such as copper, zinc cadmium, and lead in water. Reduction efficiencies of up to 90% for heavy metals and up to 99.9% for microbial load have been achieved using natural coagulants. Copper and zinc have successfully been treated to WHO drinking water standards using natural coagulants whilst the standards could not be met for manganese, lead, cadmium, chromium, arsenic, and nickel. These heavy metals for which the WHO drinking water standards were not met would require further treatment such as adsorption-based separation for further removal of the contaminants. In some cases, natural coagulants managed to remove microbial load up to 0 cfu/100mL thus achieving WHO drinking water standards. However, in some cases, the natural coagulants could not achieve total removal of microbial load and will therefore need further disinfection for the water to meet WHO standards for water quality.

Natural coagulants can maintain the pH within the range for portable water which is 6.5 to 8.5, thereby reducing costs for pH correcting which may be needed when using alum for treating water. However, when some of the plant extracts are used at the household level in conventional systems, the crude extract is used, which is not processed. In the crude extract form, the natural coagulants release organic matter and nutrients into the water which will result in the water that would have been treated decreasing its quality in terms of organic matter content. Moreover, many of the studies which have been done are lab-scale studies, with large-scale implementation at water treatment plants and commercialization being scarce.

12. Future directions

More studies are needed to address the issue of the higher levels of organic matter in the treated water when the crude form of natural coagulants is utilized for household water treatment. This is because the increased organic matter in the treated water can result in color, taste, and odor problems in the treated water and it also facilitates the development of microorganisms in the water when it is stored. Further studies are also required to come up with a way of processing and packaging coagulants from plant extracts so that they can be made available for sale as a packaged product and also to ensure that they can be stored for longer times. It is also important to investigate other plant-based coagulants which have not yet been explored such as *Elephantorrhiza goetzei* and to study the sludge produced from natural coagulants to determine whether the nitrogen and phosphorous content are enough for the sludge to be efficiently used as a soil conditioner. Furthermore, options must be explored on whether the natural coagulants can be commercially cultivated so that there will be a continuous supply of the coagulants to ensure that they can be effectively used on a large scale at water treatment plants.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

Abdo, S.M., Mahmoud, R.H., Youssef, M., El-Naggar, M.E., 2020. Cationic Starch and Polyaluminum Chloride as Coagulants for River Nile Water Treatment. Groundwater for Sustainable Development 10, 100331. https://doi.org/10.1016/j.gsd.2020.100331.

Abidin, Z.Z., Madehi, N., Yunus, R., Derahman, A., 2019. Effect of Storage Conditions on Jatropha curcas Performance as Biocoagulant for Treating Palm Oil Mill Effluent. Journal of Environmental Science and Technology 12 (2), 92–101. https://doi.org/10.3923/jest.2019.92.101.

Abo-El-Enein, S.A., Eissa, M.A., Diafullah, A.A., Rizk, M.A., Mohamed, F.M., 2011. Utilization of a low cost agro-residue for production of coagulant aids and their applications. Journal of Hazardous Materials 186 (2–3), 1200–1205. https://doi.org/10.1016/j.jhazmat.2010.11.121.

Adams, F.V., Mulaba-Bafubiandi, A.F., 2014. Application of rice hull ash for turbidity removal from water. Physics and Chemistry of the Earth 72 (September), 73–76. https://doi.org/10.1016/j.pce.2014.09.010.

Adjeroud- Abdellatif, N., Hammoui, Y., Boudria, A., Agab, S., Choulak, F., Leclerc, J.P., Merzouk, B., Madani, K., 2020. Effect of a natural coagulant extract from Opuntia ficus-indica cladode on electrocoagulation-electroflotation water treatment process. International Journal of Environmental Analytical Chemistry 00 (00), 1–25. https://doi.org/10.1080/03067319.2020.1804889.

Agarwal, P., Saini, G., 2022. Use of natural coagulants (Moringa oleifera and Benincasa hispida) for volume reduction of waste drilling slurries. Materials Today: Proceedings 49 (xxxx), 3274–3278. https://doi.org/10.1016/j.matpr.2020.12.924.

Agunbiade, M.O., Pohl, C.H., Ashafa, A.O.T., 2016. A review of the application of biofloccualnts in wastewater treatment. Polish Journal of Environmental Studies 25 (4), 1381–1389. https://doi.org/10.15244/pjoes/61063.

Ahizi, A.E., Njoku, C.N., Onyelucheya, O.E., Onyeka, M., Okonkwo, I.J., Ugochukwu, P., Chinenye, O., Igwegbe, A., 2023. Optimization of Moringa oleifera cationic protein /zeolite adsorbent blend for synthetic turbid water treatment. Sustainable Water Resources Management 9 (1), 1–12. https://doi.org/10.1007/s40899-022-00780-4.

Ahmad, A., Abdullah, S.R.S., Hasan, H.A., Othman, A.R., Ismail, N.'Izzati, 2022. Potential of local plant leaves as natural coagulant for turbidity removal. Environmental Science and Pollution Research 29 (2), 2579–2587. https://doi.org/10.1007/s11356-021-15541-7.

Ahmad, T., Ahmad, K., Alam, M., 2016. Sustainable management of water treatment sludge through 3 ' R ' concept. Journal of Cleaner Production 124, 1–13. https://doi.org/10.1016/j.jclepro.2016.02.073.

Aider, M., 2010. Chitosan application for active bio-based films production and potential in the food industry: Review. LWT - Food Science and Technology 43 (6), 837–842. https://doi.org/10.1016/j.lwt.2010.01.021.

Al-Risheq, D.I.M., Nasser, M.S., Qiblawey, H., Hussein, I.A., Benamor, A., 2021. Choline chloride based natural deep eutectic solvent for destabilization and separation of stable colloidal dispersions. Separation and Purification Technology 255, 117737.

Al-Wasify, R.S., Hamed, S.R., Ragab, S., 2023. Assessing the potential of de-oiled peanut (Arachis hypogea) seeds for surface water treatment: A sustainable alternative to chemical coagulants. Egyptian Journal of Aquatic Research xxxx, 3–8. https://doi.org/10.1016/j.ejar.2023.04.003.

Alenazi, M., Hashim, K.S., Hassan, A.A., Muradov, M., Kot, P., Abdulhadi, B., 2020. Turbidity removal using natural coagulants derived from the seeds of strychnos potatorum: Statistical and experimental approach. IOP Conference Series: Materials Science and Engineering 888 (1). https://doi.org/10.1088/1757-899X/888/1/012064.

Ali, E.N., Muyibi, S.A., Salleh, H.M., Alam, M.Z., Salleh, M.R.M., 2010. Production of Natural Coagulant from Moringa Oleifera Seed for Application in Treatment of Low Turbidity Water. Journal of Water Resource and Protection 02 (03), 259–266. https://doi.org/10.4236/jwarp.2010.23030.

Ali, S.A., Ahmad, A., 2020. Analysing water-borne diseases susceptibility in Kolkata Municipal Corporation using WQI and GIS based Kriging interpolation. GeoJournal 85 (4), 1151–1174. https://doi.org/10.1007/s10708-019-10015-3.

Aliyu, L., Mukhtar, L., Abba, S., 2015. Evaluation of Coagulation Efficiency of Natural Coagulants (Moringa Oliefera, Okra) and Alum, for Yamuna Water Treatment. In: 2nd International Conference on Science, Technology and Management, January 2015, pp. 2763–2771.

Alnawajha, M.M., Kurniawan, S.B., Imron, M.F., Abdullah, S.R.S., Hasan, H.A., Othman, A.R., 2022. Plant-based coagulants/flocculants: characteristics, mechanisms, and possible utilization in treating aquaculture effluent and benefiting from the recovered nutrients. Environmental Science and Pollution Research 29 (39), 58430–58453. https://doi.org/10.1007/s11356-022-21631-x.

Alwi, H., Idris, J., Musa, M., Ku Hamid, K.H., 2013. A preliminary study of banana stem juice as a plant-based coagulant for treatment of spent coolant wastewater. Journal of Chemistry 2013. https://doi.org/10.1155/2013/165057.

Amran, A.H., Bahrodin, M.B., Zaidi, N.S., Muda, K., Aris, A., Azrimi Umor, N., Mohd Amim, M.F., Syafiuddin, A., 2022. Turbid water treatment using deshelled carica papaya seed: Analysis via factorial design. Biointerface Research in Applied Chemistry 12 (6), 7787–7795. https://doi.org/10.33263/BRIAC126.77877795.

Amran, A.H., Zaidi, N.S., Muda, K., Bahrodin, M.B., Loan, liew W, 2021. Deshelled Carica papaya Seeds as Natural Coagulant for Improvement Quality of River Water. Sains Malaysiana 50 (6), 1521–1529. https://doi.org/10.17576/jsm-2021-5006-02.

Andrade, P.V., Palanca, C.F., de Oliveira, M.A.C., Ito, C.Y.K., dos Reis, A.G., 2021. Use of Moringa oleifera seed as a natural coagulant in domestic wastewater tertiary treatment: Physicochemical, cytotoxicity and bacterial load evaluation. Journal of Water Process Engineering 40 (October 2020). https://doi.org/10.1016/j.jwpe.2020.101859.

Ang, W.L., Mohammad, A.W., 2020. State of the art and sustainability of natural coagulants in water and wastewater treatment. Journal of Cleaner Production 262, 121267. https://doi.org/10.1016/j.jclepro.2020.121267.

Anwar, F., Yaqout, A., 2003. Assessment and analysis of industrial liquid waste and sludge disposal at unlined landfill sites in arid climate. Waste Management 23 (9), 817–824. https://doi.org/10.1016/S0956-053X(03)00036-9.

Araújo, L.C.C., Aguiar, J.S., Napoleão, T.H., Mota, F.V.B., Barros, A.L.S., Moura, M.C., Coriolano, M.C., Coelho, L.C.B.B., Silva, T.G., Paiva, P.M.G., 2013. Evaluation of cytotoxic and anti-inflammatory activities of extracts and lectins from Moringa oleifera seeds. PLoS ONE 8 (12), 1–15. https://doi.org/10.1371/journal.pone.0081973.

Arnoldsson, E., Bergman, M., Matsinhe, N., others, 2008. Assessment of drinking water bark extracts of Moringa oleifera in reducing bacterial load in water. Int J Adv Res 4, 124–130.

Arshad, N., Imran, S., 2020. Current Research in Green and Sustainable Chemistry Indigenous waste plant materials: An easy and cost-effective approach for the removal of heavy metals from water. Current Research in Green and Sustainable Chemistry 3 (October), 100040. https://doi.org/10.1016/j.crgsc.2020.100040.

Aryal, J., Gautam, B., Sapkota, N., 2012. Drinking water quality assessment. Journal of Nepal Health Research Council 10 (22), 192–196.

Ashbolt, N.J., 2004. Microbial contamination of drinking water and disease outcomes in developing regions. Toxicology 198 (1–3), 229–238. https://doi.org/10.1016/j.tox.2004.01.030.

Asrafuzzaman, M., Fakhruddin, A.N.M., Hossain, M.A., 2011. Reduction of Turbidity of Water Using Locally Available Natural Coagulants. ISRN Microbiology 1–6. https://doi.org/10.5402/2011/632189.

Babu, R., & Chaudhuri, M. (2005). Home water treatment by direct filtration with natural coagulant Raveendra Babu and Malay Chaudhuri. 27–30.

Bahrodin, M.B., Zaidi, N.S., Hussein, N., Sillanpää, M., Prasetyo, D.D., Syafiuddin, A., 2021. Recent Advances on Coagulation-Based Treatment of Wastewater: Transition from Chemical to Natural Coagulant. Current Pollution Reports 7 (3), 379–391. https://doi.org/10.1007/s40726-021-00191-7.

Behera, B., Balasubramanian, P., 2019. Natural plant extracts as an economical and ecofriendly alternative for harvesting microalgae. Bioresource Technology 283 (January), 45–52. https://doi.org/10.1016/j.biortech.2019.03.070.

Bekele, D., Yegrem, L., 2021. Levels of Heavy Metal in Vegetable, Fruits and Cereals Crops in Ethiopia: A Review. International Journal of Environmental Monitoring and Analysis 9 (4), 96. https://doi.org/10.11648/j.ijema.20210904.11.

Beljon, R., 2021. Towards simulations on the dynamics of colloidal coagulation MSc thesis. Eindhoven University of Technology.

Benabid, F.Z., Zouai, F, 2016. Naturalpolymers:Cellulose, Chitin,Chitosan,Gelatin,Starch, Garrageenan,Xylan and Dextran. Algerian Journal of Natural Products 4 (3), 348–357.

Benalia, A., Derbal, K., Panico, A., Pirozzi, F., 2018. Use of acorn leaves as a natural coagulant in a drinking water treatment plant. Water (Switzerland) 11 (1), 1–12. https://doi.org/10.3390/w11010057.

Beyene, H.D., Hailegebrial, T.D., Dirersa, W.B., 2016. Investigation of Coagulation Activity of Cactus Powder in Water Treatment. Journal of Applied Chemistry 2016, 8–9, 10.1080/23311916.2017.1365676.

Birima, A.H., Ahmed, A.T., Noor, M.J.M.M., Sidek, L.M., Muda, Z.C., Wong, L.S., 2015. Application of salt extracted peanut seeds in the pretreatment of palm oil mill effluent (POME). Desalination and Water Treatment 55 (8), 2196–2200. https://doi.org/10.1080/19443994.2014.930696.

Birima, A.H., Hammad, H.A., Desa, M.N.M., Muda, Z.C., 2013. Extraction of natural coagulant from peanut seeds for treatment of turbid water. IOP Conference Series: Earth and Environmental Science 16 (1). https://doi.org/10.1088/1755-1315/16/1/012065.

Boelee, E., Geerling, G., van der Zaan, B., Blauw, A., Vethaak, A.D., 2019. Water and health: From environmental pressures to integrated responses. Acta Tropica 193 (February 2018), 217–226. https://doi.org/10.1016/j.actatropica.2019.03.011.

Bordi, F., Cametti, C., Colby, R.H., 2004. Dielectric spectroscopy and conductivity of polyelectrolyte solutions. Journal of Physics Condensed Matter 16 (49). https://doi.org/10.1088/0953-8984/16/49/R01.

Botany Today. (2018). Plantago Ovata. https://www.botanytoday.com/plantago-ovata/.

Bouchareb, R., Derbal, K., Benalia, A., 2021. Optimization of active coagulant agent extraction method from Moringa Oleifera seeds for municipal wastewater treatment. Water Science and Technology 84 (2), 393–403. https://doi.org/10.2166/wst.2021.234.

Bouchareb, R., Derbal, K., Özay, Y., Bilici, Z., Dizge, N., 2020. Combined natural/chemical coagulation and membrane filtration for wood processing wastewater treatment. Journal of Water Process Engineering 37 (July), 101521. https://doi.org/10.1016/j.jwpe.2020.101521.

Bradney, L., Wijesekara, H., Palansooriya, K.N., Obadamudalige, N., Bolan, N.S., Ok, Y.S., Rinklebe, J., Kim, K.H., Kirkham, M.B., 2019. Particulate plastics as a vector for toxic trace-element uptake by aquatic and terrestrial organisms and human health risk. Environment International 131, 104937.

Burgos-vergara, J., Lugo-arias, E., & Gould, A. (2020). Evaluation of low-cost alternatives for water purifi cation in the stilt house villages of Santa Marta ' s Ci enaga Grande. 6 (October 2019). doi:10.1016/j.heliyon.2019.e03062.

Camacho, F.P., Sousa, V.S., Bergamasco, R., Ribau Teixeira, M., 2017. The use of Moringa oleifera as a natural coagulant in surface water treatment. Chemical Engineering Journal 313, 226–237. https://doi.org/10.1016/j.cej.2016.12.031.

Chong, J.W.R., Khoo, K.S., Yew, G.Y., Leong, W.H., Lim, J.W., Lam, M.K., Ho, Y.C., Ng, H.S., Munawaroh, H.S.H., Show, P.L., 2021. Advances in production of bioplastics by microalgae using food waste hydrolysate and wastewater: A review. Bioresource Technology 342, 125947.

Choudhary, M., Neogi, S., 2017. A natural coagulant protein from Moringa Oleifera: Isolation, characterization, and potential use for water treatment. Materials Research Express.

Choudhary, M., Ray, M.B., Neogi, S., 2018. Evaluation of the potential application of cactus (Opuntia ficus-indica) as a bio-coagulant for pre-treatment of oil sands process-affected water. Separation and Purification Technology 209, 714–724. https://doi.org/10.1016/j.seppur.2018.09.033.

Choy, S.Y., Prasad, K.M.N., Wu, T.Y., Raghunandan, M.E., Ramanan, R.N., 2014. Utilization of plant-based natural coagulants as future alternatives towards sustainable water clarification. Journal of Environmental Sciences (China) 26 (11), 2178–2189. https://doi.org/10.1016/j.jes.2014.09.024.

Choy, S.Y., Prasad, K.M.N., Wu, T.Y., Ramanan, R.N., 2015. A review on common vegetables and legumes as promising plant-based natural coagulants in water clarification. International Journal of Environmental Science and Technology 12, 367–390.

Cinthura, C., Gayathri, R., Priya, V., 2017. Genotoxicity analysis of mace (Myristica fragrans) on oral cancer cell line by DNA fragmentation. Journal of Pharmaceutical Sciences and Research 9 (2), 205–207.

Çoruh, H.A., 2005. Use of Calcium Alginate As a Coagulant in Water Treatment. Middle East Technical University.

Dayarathne, H.N.P., Angove, M.J., Aryal, R., Abuel-naga, H., Mainali, B., 2021. Journal of Water Process Engineering Removal of natural organic matter from source water: Review on coagulants, dual coagulation, alternative coagulants, and mechanisms. Journal of Water Process Engineering 40 (November 2020), 101820. https://doi.org/10.1016/j.jwpe.2020.101820.

de Souza, M.T.F., de Almeida, C.A., Ambrosio, E., Santos, L.B., Freitas, T.K.F., de, S., Manholer, D.D., de Carvalho, G.M., Garcia, J.C., 2016. Extraction and use of Cereus peruvianus cactus mucilage in the treatment of textile effluents. Journal of the Taiwan Institute of Chemical Engineers 67 (October), 174–183. https://doi.org/10.1016/j.jtice.2016.07.009.

Dhivya, S., Ramesh, S.T., Gandhimathi, R., Nidheesh, P.V., 2017. Performance of Natural Coagulant Extracted from Plantago ovata Seed for the Treatment of Turbid Water. Water, Air, and Soil Pollution 228 (11). https://doi.org/10.1007/s11270-017-3592-1.

Dibyangana, D.S., Varsha, J.M., Vilasrao, K.J., 2015. Chitosan: a propitious biopolymer for drug delivery. Current Drug Delivery 12 (4), 369–381.

Doppalapudi, S. C. (2019). Anti-inflammatory activity of Cicer arietinum seed extracts Academic Sciences Asian Journal of Pharmaceutical and Clinical Research. February.

Dorca, J., Veit, M.T., Juchen, P.T., Gonçalves, C., Moreno, S., Fagundes-klen, M., 2018. Journal of Environmental Chemical Engineering Use of di ff erent coagulants for cassava processing wastewater treatment. Journal of Environmental Chemical Engineering 6 (2), 1821–1827. https://doi.org/10.1016/j.jece.2018.02.039.

Duranti, M., Gius, C., 1997. Legume seeds: Protein content and nutritional value. Field Crops Research 53 (1–3), 31–45. https://doi.org/10.1016/S0378-4290(97)00021-X.

Dursun, S., Sarcan, A., 2022. Determination of water quality in Hadim District of Konya (Turkey) and the investigation of disinfection efficiency. Advanced Engineering Science 2, 101–108.

Edokpayi, J. N., Odiyo, J. O., & Durowoju, O. S. (2017). Household Hazardous Waste Management in - Impact of Wastewater on Surface Water Quality in sub-Saharan Africa Developing Countries: A Case Study of South Africa. 18, 1–16.

El-taweel, R.M., Mohamed, N., Alrefaey, K.A., Husien, S., Abdel-aziz, A.B., Salim, A.I., Mostafa, N.G., Said, L.A., Samy, I., Radwan, A.G., 2023. Current Research in Green and Sustainable Chemistry A review of coagulation explaining its de fi nition, mechanism, coagulant types, and optimization models; RSM, and ANN. Current Research in Green and Sustainable Chemistry 6 (January), 100358. https://doi.org/10.1016/j.crgsc.2023.100358.

Elsayed, E.M., Nour El-Den, A.A., Elkady, M.F., Zaatout, A.A, 2020. Comparison of coagulation performance using natural coagulants against traditional ones. Separation Science and Technology (Philadelphia) 1–9. https://doi.org/10.1080/01496395.2020.1795674, 00(00).

Exporters India. (2022). Dolichos Lablab Seeds (Lablab Purpureus). https://www.exportersindia.com/product-detail/dolichos-lablab-seeds-lablab-purpureus-2715605.htm.

Fawell, J., Bailey, K., Chilton, J., Dahi, E., Fewtrell, L., & Magara, Y. (2001). Flouride in Drinking-water. http://www.who.int/bookorders.

Fernando, W.A.M., Ilankoon, I.M.S.K., Syed, T.H., Yellishetty, M., 2018. Challenges and opportunities in the removal of sulphate ions in contaminated mine water: A review. Minerals Engineering 117 (November 2017), 74–90. https://doi.org/10.1016/j.mineng.2017.12.004.

Ferreira, R.S., Napoleão, T.H., Santos, A.F.S., Sá, R.A., Carneiro-da-Cunha, M.G., Morais, M.M.C., Silva-Lucca, R.A., Oliva, M.L.V., Coelho, L.C.B.B., Paiva, P.M.G., 2011. Coagulant and antibacterial activities of the water-soluble seed lectin from Moringa oleifera. Letters in Applied Microbiology 53 (2), 186–192. https://doi.org/10.1111/j.1472-765X.2011.03089.x.

Foidl, N., Makkar, H. P. S., Becker, K., Foild, N., & Km, S. (2001). The potential of Moringa oleifera for agricultural and industrial uses.

Freitas, T. K. F. S., Almeida, C. A., Manholer, D. D., Geraldino, H. C. L., de Souza, M. T. F., & Garcia, J. C. (2018). Review of Utilization Plant-Based Coagulants as Alternatives to Textile Wastewater Treatment. doi:10.1007/978-981-10-4780-0_2.

Gandiwa, B.I., Moyo, L.B., Ncube, S., Mamvura, T.A., Mguni, L.L., Hlabangana, N., 2020. Optimisation of using a blend of plant based natural and synthetic coagulants for water treatment: (Moringa Oleifera-Cactus Opuntia-alum blend). South African Journal of Chemical Engineering 34 (July), 158–164. https://doi.org/10.1016/j.sajce.2020.07.005.

Gao, B.Y., Hahn, H.H., Hoffmann, E., 2002. Evaluation of aluminum-silicate polymer composite as a coagulant for water treatment. Water Research 36 (14), 3573–3581. https://doi.org/10.1016/S0043-1354(02)00054-4.

García-Fayos, B., Arnal, J.M., Sancho, M., Rodrigo, I., 2016. Moringa oleifera for drinking water treatment: influence of the solvent and method used in oil-extraction on the coagulant efficiency of the seed extract. Desalination and Water Treatment 57 (48–49), 23397–23404.

Gautam, S., Saini, G., 2020. Use of natural coagulants for industrial wastewater treatment. Global Journal of Environmental Science and Management 6 (4), 553–578. https://doi.org/10.22034/gjesm.2020.04.10.

Gerald, Buff, C, 2002. Image of Maerua subcordata (Gilg) De Wolf. California Academy of Sciences.

Ghernaout, D., Elboughdiri, N., Ghareba, S., Salih, A., 2020. Coagulation Process for Removing Algae and Algal Organic Matter—An Overview. OALib 07 (04), 1–21. https://doi.org/10.4236/oalib.1106272.

Gomes, L., Troiani, E.P., Malpass, G.R.P., Nozaki, J., 2016. Opuntia ficus indica as a polyelectrolyte source for the treatment of tannery wastewater. Desalination and Water Treatment 57 (22), 10181–10187. https://doi.org/10.1080/19443994.2015.1035677.

Hadadi, A., Imessaoudene, A., Bollinger, J.C., Assadi, A.A., Amrane, A., Mouni, L., 2022. Comparison of Four Plant-Based Bio-Coagulants Performances against Alum and Ferric Chloride in the Turbidity Improvement of Bentonite Synthetic Water. Water (Switzerland) 14 (20). https://doi.org/10.3390/w14203324.

Halder, A., 2021. Bio-coagulants, a substitute of chemical coagulants. Journal of Advanced Scientific Research 12 (4), 58–67.

Hamawand, I., Ghadouani, A., Bundschuh, J., Hamawand, S., Al Juboori, R.A., Chakrabarty, S., Yusaf, T., 2017. A critical review on processes and energy profile of the Australian meat processing industry. Energies 10 (5), 1–29. https://doi.org/10.3390/en10050731.

Hashim, U., Al-Mufti, M.W., Adamand, T., Hussein, M.A., 2013. Plant seeds-potential alternative as natural coagulant to treat water for turbidity. Journal of Applied Sciences Research 9 (2), 1067–1073.

Hassan, R.A.M., 2005. Effect of Aluminum Chloro Hydrate Treatment on the Physiochemical Properties of River Nile Water at Omdurman, Sudan. University of Gezira.

Heiderscheidt, E., Leiviskä, T., Ronkanen, A.K., Kløve, B., 2016. Evaluating the suitability of synthetic organic polymers to replace iron salts in the purification of humic and sediment-rich runoff. Desalination and Water Treatment 57 (23), 10948–10957. https://doi.org/10.1080/19443994.2015.1043954.

Ho, Y.C., Norli, I., Alkarkhi, A.F., Morad, N., 2014. New vegetal biopolymeric flocculant: A degradation and flocculation study. Iran. J. Energy Environ 5 (1), 26–33.

Hoa, N.T., Hue, C.T., 2018. Enhanced water treatment by moringa oleifera seeds extract as the bio-coagulant: Role of the extraction method. Journal of Water Supply: Research and Technology - AQUA 67 (7), 634–647. https://doi.org/10.2166/aqua.2018.070.

Hussain, S., Ghouri, A.S., Ahmad, A., 2019. Pine cone extract as natural coagulant for purification of turbid water. Heliyon 5 (3), e01420. https://doi.org/10.1016/j.heliyon.2019.e01420.

Hussian, S., Mane, V., Pradhan, V., Faroogui, M., 2012. Efficiency of seeds of Moringa oleifera in estimation of water turbidity. Int J Res Pharmaceut Biomed Sci 3 (3), 1334–1337.
Huzir, N.M., Aziz, M.M.A., Ismail, S.B., Mahmood, N.A.N., Umor, N.A., Faua'ad Syed Muhammad, S.A., 2019. Optimization of coagulation-flocculation process for the palm oil mill effluent treatment by using rice husk ash. Industrial Crops and Products 139 (May), 111482. https://doi.org/10.1016/j.indcrop.2019.111482.
Igbokwe, N.H., Ogbonnia, S.O., Azubuike, C.P., Idowu, A.O., Orajiaka, S.C., Ota, D.A., 2018. Acute and sub-chronic toxicities and antimicrobial profiling of hydro-ethanol extracts of Moringa oleifera (L) seed in swiss albino mice and wistar rats. Tropical Journal of Natural Product Research 2 (7), 362–369. https://doi.org/10.26538/tjnpr/v2i7.11.
Iwuozor, K.O., 2019. Prospects and Challenges of Using Coagulation-Flocculation method in the treatment of Effluents. Advanced Journal of Chemistry-Section A 2 (2), 105–127. https://doi.org/10.29088/sami/ajca.2019.2.105127.
Jagaba, A.H., Kutty, S.R.M., Hayder, G., Latiff, A.A.A., Aziz, N.A.A., Umaru, I., Ghaleb, A. A.S., Abubakar, S., Lawal, I.M., Nasara, M.A., 2020. Sustainable use of natural and chemical coagulants for contaminants removal from palm oil mill effluent: A comparative analysis. Ain Shams Engineering Journal 11 (4), 951–960. https://doi.org/10.1016/j.asej.2020.01.018.
Johnson, K. M., & Elphinston, A. J. (2017). Storage, Clarification and Chemical Treatment 8 8.1 (pp. 323–366). doi:10.1016/B978-0-08-100025-0.00008-9.
Jones, A.N., Bridgeman, J., 2016. An assessment of the use of native and denatured forms of okra seed proteins as coagulants in drinking water treatment. Journal of Water and Health 14 (5), 768–779. https://doi.org/10.2166/wh.2016.015.
Kabir, M. M., Science, N., & Sarker, P. (2019). Removal of iron and turbidity from ground water by natural and chemical coagulants Removal of iron and turbidity from ground water by natural and chemical coagulants. May 2021.
Kahlson, M.A., Dixon, S.J., 2022. Copper-induced cell death. Science 375 (6586), 1231–1232.
Kaji, A., Taheriyoun, M., Taebi, A., Nazari-Sharabian, M., 2020. Comparison and optimization of the performance of natural-based non-conventional coagulants in a water treatment plant. Journal of Water Supply: Research and Technology - AQUA 69 (1), 28–38. https://doi.org/10.2166/aqua.2019.075.
Kakoi, B., Kaluli, J.W., Ndiba, P., Thiong'o, G., 2016. Banana pith as a natural coagulant for polluted river water. Ecological Engineering 95, 699–705. https://doi.org/10.1016/j.ecoleng.2016.07.001.
Kangama, A., Zeng, D., Tian, X., Fang, J., 2018. Application of Chitosan Composite Flocculant in Tap Water Treatment. Journal of Chemistry 2018 (Dd). https://doi.org/10.1155/2018/2768474.
Kanmani, P., Aravind, J., Kamaraj, M., Sureshbabu, P., Karthikeyan, S., 2017. Environmental applications of chitosan and cellulosic biopolymers: A comprehensive outlook. Bioresource Technology 242, 295–303. https://doi.org/10.1016/j.biortech.2017.03.119.
Kass, A., Gavrieli, I., Yechieli, Y., Vengosh, A., Starinsky, A., 2005. The impact of freshwater and wastewater irrigation on the chemistry of shallow groundwater: A case study from the Israeli Coastal Aquifer. Journal of Hydrology 300 (1–4), 314–331. https://doi.org/10.1016/j.jhydrol.2004.06.013.
Keeley, J., Jarvis, P., Judd, S.J., 2012. An economic assessment of coagulant recovery from water treatment residuals. Desalination 287, 132–137. https://doi.org/10.1016/j.desal.2011.09.013.
Koshani, R., Tavakolian, M., van de Ven, T.G.M., 2020. Cellulose-based dispersants and flocculants. Journal of Materials Chemistry B 8 (46), 10502–10526.
Kristianto, H., 2017. The Potency of Indonesia Native Plants as Natural Coagulant: a Mini Review. Water Conservation Science and Engineering 2 (2), 51–60. https://doi.org/10.1007/s41101-017-0024-4.
Kristianto, H., Kurniawan, M.A., Soetedjo, J.N.M., 2018. Utilization of Papaya Seeds as natural coagulant for synthetic textile coloring agent wastewater treatment. International Journal on Advanced Science, Engineering and Information Technology 8 (5), 2071–2077. https://doi.org/10.18517/ijaseit.8.5.3804.
Krupinska, I., 2020. Aluminium Drinking Water Treatment Residuals and Their Toxic Impact on Human Health. Molecules 25 (3), 13.
Kumar, M., Selvasekaran, P., Kapoor, S., Barbhai, M.D., Lorenzo, J.M., Saurabh, V., Potkule, J., Changan, S., ElKelish, A., Selim, S., Sayed, A.A.S., Radha, Singh, S., Senapathy, M., Pandiselvam, R., Dey, A., Dhumal, S., Natta, S., Amarowicz, R., Kennedy, J.F, 2022. Moringa oleifera Lam. seed proteins: Extraction, preparation of protein hydrolysates, bioactivities, functional food properties, and industrial application. Food Hydrocolloids 131 (January), 107791. https://doi.org/10.1016/j.foodhyd.2022.107791.
Kumar, V., Othman, N., Asharuddin, S., 2017. Applications of Natural Coagulants to Treat Wastewater - A Review. In: MATEC Web of Conferences, 103, pp. 1–9. https://doi.org/10.1051/matecconf/201710306016.
Kurniawan, S.B., Abdullah, S.R.S., Imron, M.F., Said, N.S.M., Ismail, N.'Izzati, Hasan, H. A., Othman, A.R., Purwanti, I.F, 2020. Challenges and opportunities of biocoagulant/bioflocculant application for drinking water and wastewater treatment and its potential for sludge recovery. International Journal of Environmental Research and Public Health 17 (24), 1–33. https://doi.org/10.3390/ijerph17249312.
Kurniawan, S. B., Ahmad, A., Imron, M. F., Rozaimah, S., Abdullah, S., Hasan, H. A., & Othman, A. R. (2023). Performance of Chemical-Based vs Bio-Based Coagulants in Treating Aquaculture Wastewater and Cost-b enefit Analysis. 32(2), 1177–1187. doi:10.15244/pjoes/156419.
Lee, D.J., Chang, Y.R., 2018. Bioflocculants from isolated stains: A research update. Journal of the Taiwan Institute of Chemical Engineers 87, 211–215. https://doi.org/10.1016/j.jtice.2018.03.037.
Lu, J., Zhang, J., Yin, F., 2018. Enhanced Coagulation for the Different Mixture Ratio Raw Water of Yellow River Water and South-to-North Water Diversion Water. IOP Conference Series: Earth and Environmental Science 178 (1). https://doi.org/10.1088/1755-1315/178/1/012010.
Maćczak, P., Kaczmarek, H., Ziegler-Borowska, M., Węgrzynowska-Drzymalska, K., Burkowska-But, A., 2022. The use of chitosan and starch-based flocculants for filter backwash water treatment. Materials 15 (3), 1056.
Makarfi, Z.Y., Ali, M., Mu'azu, L., Sudawa, R.H., 2022. Application of Moringa oleifera Seeds Extracts in Purification of Ground Water. South Asian Res J Bio Appl Biosci 4 (3), 68–72.
Mane, P., Bhosle, A. S., & Jangam, C. (2011). Heavy Metal Removal from Aqueous Solution by Opuntia: A Natural Polyelectrolyte Heavy Metal Removal from Aqueous Solution by Opuntia: A Natural Polyelectrolyte. January.
Marey, A.M., 2019. Effectiveness of chitosan as natural coagulant in treating turbid waters. Revista Bionatura 4 (2), 856–860. https://doi.org/10.21931/RB/2019.04.02.7.
Marobhe, N.J., Sabai, S.M., 2021. Treatment of drinking water for rural households using moringa seed and solar disinfection. Journal of Water Sanitation and Hygiene for Development 11 (4), 579–590. https://doi.org/10.2166/washdev.2021.253.
Marobhe, N., Renman, G., Jackson, M., 2007. Investigation on the performance of local plant materials for coagulation of turbid river water. Journal of the Institution of Engineers Tanzania 8 (3), 50–62.
Mcallister, S., 2005. Analysis and comparison of sustainable water filters. United Nations 2005, 22.
Megersa, M., Beyene, A., Ambelu, A., Asnake, D., Bekele, T., Firdissa, B., Alebachew, Z., Triest, L., 2016. A Preliminary Evaluation of Locally Used Plant Coagulants for Household Water Treatment. Water Conservation Science and Engineering 1 (2), 95–102. https://doi.org/10.1007/s41101-016-0006-y.
Megersa, M., Beyene, A., Ambelu, A., Triest, L., 2019. Coupling Extracts of Plant Coagulants With Solar Disinfection Showed a Complete Inactivation of Faecal Coliforms. Clean - Soil, Air, Water 47 (1). https://doi.org/10.1002/clen.201700450.
Melinda, V., Dewi, I., Rahmayanti, M., 2022. Indonesian Journal of Chemical Research 10 (1), 14–18. https://doi.org/10.30598//ijcr.2022.10-vin.
Meneghel, A.P., Gonçalves, A.C., Rubio, F., Dragunski, D.C., Lindino, C.A., Strey, L., 2013. Biosorption of cadmium from water using moringa (Moringa oleifera Lam.) Seeds. Water, Air, and Soil Pollution 224 (3), 1–13. https://doi.org/10.1007/s11270-012-1383-2.
Mohd-Salleh, S.N.A., Mohd-Zin, N.S., Othman, N., 2019. A review of wastewater treatment using natural material and its potential as aid and composite coagulant. Sains Malaysiana 48 (1), 155–164.
Moringa Matters. (2022). How to grow an African Moringa tree in Florida. https://www.moringamatters.com/how-to-grow-an-African-Moringa-tree-in-Florida.html.
Mortadi, A., Chahid, E.G., Nasrellah, H., Cherkaoui, O., El Moznine, R., 2017. Dielectric and electric properties as a tool to investigate the coagulation mechanism during sludge treatment. Environmental Technology (United Kingdom) 40 (1), 72–85. https://doi.org/10.1080/09593330.2017.1378927.
Mumbi, A.W., Fengting, L., Karanja, A., 2018. Sustainable treatment of drinking water using natural coagulants in developing countries: A case of informal settlements in Kenya. Water Utility Journal 18 (October), 1–11. https://doi.org/10.13140/RG.2.2.21105.94563.
Naceradska, J., Pivokonska, L., & Pivokonsky, M. (2019). On the importance of pH value in coagulation. 222–230. doi:10.2166/aqua.2019.155.
Nand, V., Maata, M., Koshy, K., Sotheeswaran, S., 2012. Water Purification using Moringa oleifera and Other Locally Available Seeds in Fiji for Heavy Metal Removal. International Journal of Applied Science and Technology 2 (5), 125–129.
Napacho, Z.A., Manyele, S.V., 2010. Quality assessment of drinking water in Temeke District (part II): Characterization of chemical parameters. African Journal of Environmental Science and Technology 4 (11), 775–789.
Ndabigengesere, A., Narasiah, K.S., Talbot, B.G., 1995. Active agents and mechanism of coagulation of turbid waters using Moringa oleifera. Water Research 29 (2), 703–710. https://doi.org/10.1016/0043-1354(94)00161-Y.
Ndibewu, P.P., Mnisi, R.L., Mokgalaka, S.N., McCrindle, R.I., 2011. Heavy metal removal in aqueous systems using Moringa oleifera: a review. Journal of Materials Science and Engineering. B 1 (6B), 843.
Neksumi, M., Zishan, M., Sushmita, B., Manzoor, U., 2022. The Global Menace of Hazardous Waste: Challenges and Management. Handbook of Solid Waste Management. Springer, pp. 1715–1742.
Neukirchen, F., Ries, G., 2020. Industrial Minerals and Rocks. The World of Mineral Deposits. Springer, pp. 325–340.
Nharingo, T., Zivurawa, M.T., Guyo, U., 2015. Exploring the use of cactus Opuntia ficus indica in the biocoagulation–flocculation of Pb(II) ions from wastewaters. International Journal of Environmental Science and Technology 12 (12), 3791–3802. https://doi.org/10.1007/s13762-015-0815-0.
Nhut, H.T., Hung, N.T.Q., Lap, B.Q., Han, L.T.N., Tri, T.Q., Bang, N.H.K., Hiep, N.T., Ky, N.M., 2021. Use of Moringa oleifera seeds powder as bio-coagulants for the surface water treatment. International Journal of Environmental Science and Technology 18 (8), 2173–2180. https://doi.org/10.1007/s13762-020-02935-2.
Nisa, A.M., Kishor, B., 2021. Removal of Turbidity and TDS from Wastewater by Using Natural Coagulants - A Review. IOP Conference Series: Earth and Environmental Science 889 (1). https://doi.org/10.1088/1755-1315/889/1/012074.
Nouhi, S., Kwaambwa, H.M., Gutfreund, P., Rennie, A.R., 2019. Comparative study of flocculation and adsorption behaviour of water treatment proteins from Moringa peregrina and Moringa oleifera seeds. Scientific Reports 9 (1), 17945. https://doi.org/10.1038/s41598-019-54069-2.
Nwaiwu, N.E., Lingmu, B., 2011. Effect of settling time on turbidity removal using Moringa oleifera seed powder. Ozean J Appl Sci 4 (3), 195–208.

Ojha, A. (2020). Materials in Electrochemical Detection of Water Pollutants. doi:10.1007/978-981-15-0671-0_10.
Okuda, T., Baes, A.U., Nishijima, W., Okada, M., 1999. Improvement of extraction method of coagulation active components from Moringa oleifera seed. Water Research 33 (15), 3373–3378. https://doi.org/10.1016/S0043-1354(99)00046-9.
Okuda, T., Baes, A.U., Nishijima, W., Okada, M., 2001. Isolation and characterization of coagulant extracted from Moringa oleifera seed by salt solution. Water Research 35 (2), 405–410. https://doi.org/10.1016/S0043-1354(00)00290-6.
Okunlola, M.B., Ijah, U.J.J., Yisa, J., Abioye, P.O., Ariyeloye, D.S., Ibrahim, J.N., 2020. Purification efficacy of different parts of Mangifera indica on water samples from contaminated drinking water sources in chanchaga local government area of Niger State, Nigeria. Applied Water Science 10 (4), 1–11. https://doi.org/10.1007/s13201-020-01183-6.
Oladoja, N.A., 2015. Headway on natural polymeric coagulants in water and wastewater treatment operations. Journal of Water Process Engineering 6, 174–192. https://doi.org/10.1016/j.jwpe.2015.04.004.
Oluduro, O.A., Aderiye, B.I., Connolly, J.D., Akintayo, E.T., Famurewa, O., 2010. Characterization and Antimicrobial Activity of 4-(β-d-Glucopyranosyl-1→4-α-L-rhamnopyranosyloxy)-benzyl thiocarboxamide; a Novel Bioactive Compound from Moringa oleifera Seed Extract. Folia Microbiologica 55 (5), 422–426. https://doi.org/10.1007/s12223-010-0071-0.
Omran, I.I., Al-Saati, N.H., Al-Saati, H.H., Hashim, K.S., Al-Saati, Z.N, 2021. Sustainability assessment of wastewater treatment techniques in urban areas of iraq using multi-criteria decision analysis (Mcda). Water Practice and Technology 16 (2), 648–660. https://doi.org/10.2166/wpt.2021.013.
Owodunni, A.A., Ismail, S., Kurniawan, S.B., Ahmad, A., Imron, M.F., Abdullah, S.R.S., 2023. A review on revolutionary technique for phosphate removal in wastewater using green coagulant. Journal of Water Process Engineering 52, 103573.
Paisley Farm & Crafts. (2022). Wholesale Moringa Oleifera PKM1 Seeds - US Customs Cleared - All Natural! https://paisleyfc.com/wholesale-moringa-oleifera-pkm1-seeds-us-customs-cleared-all-natural/.
Pal, M., Ayele, Y., Hadush, A., Panigrahi, S., Jadhav, V.J., 2018. Public Health Hazards Due to Unsafe Drinking Water. Air & Water Borne Diseases 7 (June), 1–6. https://doi.org/10.4172/2167-7719.1000138.
Pandey, D., Verma, S., Verma, P., Mahanty, B., Dutta, K., Daverey, A., Arunachalam, K., 2021. SARS-CoV-2 in wastewater: challenges for developing countries. International Journal of Hygiene and Environmental Health 231, 113634.
Pandey, P., Khan, F., Mishra, R., Singh, S.K., 2020. Elucidation of the potential of Moringa oleifera leaves extract as a novel alternate to the chemical coagulant in water treatment process. Water Environment Research 92 (7), 1051–1056. https://doi.org/10.1002/wer.1300.
Patchaiyappan, A., Devipriya, S.P., 2021. Application of plant-based natural coagulants in water treatment. Cost Effective Technologies for Solid Waste and Wastewater Treatment. Elsevier Inc. https://doi.org/10.1016/B978-0-12-822933-0.00012-7.
Patchaiyappan, A., Sarangapany, S., Saksakom, Y.A., Devipriya, S.P., 2020. Feasibility study of a point of use technique for water treatment using plant-based coagulant and isolation of a bioactive compound with bactericidal properties. Separation Science and Technology 55 (1), 112–122.
Peter, J.K., Kumar, Y., Pandey, P., Masih, H., 2014. Antibacterial Activity of Seed and Leaf Extract of Carica Papaya var. Pusa dwarf Linn. IOSR Journal of Pharmacy and Biological Sciences 9 (2), 29–37. https://doi.org/10.9790/3008-09272937.
Phillip, M.J., 2013. Combating Water Scarcity in Southern Africa: Case Studies from Namibia. Springer.
Price, M. L. (2007). The Moringa Tree. Echo Technical Note.
Pritchard, M., Mkandawire, T., Edmondson, A., O'Neill, J.G., Kululanga, G., 2009. Potential of using plant extracts for purification of shallow well water in Malawi. Physics and Chemistry of the Earth 34 (13–16), 799–805. https://doi.org/10.1016/j.pce.2009.07.001.
Rajoria, S., Vashishtha, M., Sangal, V.K., 2022. Treatment of electroplating industry wastewater: a review on the various techniques. Environmental Science and Pollution Research 29 (48), 72196–72246.
Ramavandi, B., 2014. Treatment of water turbidity and bacteria by using a coagulant extracted from Plantago ovata. Water Resources and Industry 6, 36–50. https://doi.org/10.1016/j.wri.2014.07.001.
Ramavandi, B., Hashemi, S., Kafaei, R., 2015. A novel method for extraction of a proteinous coagulant from Plantago ovata seeds for water treatment purposes. MethodsX 2, 278–282. https://doi.org/10.1016/j.mex.2015.05.006.
Rayudu, E.S., Likhitha, A., Reddy, K.S., Nagesh Kumar, G., 2022. A Study on Dragon Fruit Foliage as Natural Coagulant and Coagulant Aid for Water Treatment. IOP Conference Series: Earth and Environmental Science 982 (1). https://doi.org/10.1088/1755-1315/982/1/012040.
Righetto, I., Al-juboori, R.A., Uzkurt, J., Mikola, A., 2021. Journal of Environmental Chemical Engineering Multipurpose treatment of landfill leachate using natural coagulants – Pretreatment for nutrient recovery and removal of heavy metals and micropollutants. Journal of Environmental Chemical Engineering 9 (3), 105213. https://doi.org/10.1016/j.jece.2021.105213.
Rolim, L.A.D.M.M., Macêdo, M.F.S., Sisenando, H.A., Napoleão, T.H., Felzenszwalb, I., Aiub, C.A.F., Coelho, L.C.B.B., Medeiros, S.R.B., Paiva, P.M.G., 2011. Genotoxicity Evaluation of Moringa oleifera Seed Extract and Lectin. Journal of Food Science 76 (2). https://doi.org/10.1111/j.1750-3841.2010.01990.x.
Sadeghi, N., Moghaddam, J., Ilkhchi, M.O.jagh, 2017. Determination of effective parameters in pilot plant scale direct leaching of a zinc sulfide concentrate. Physicochemical Problems of Mineral Processing 53 (1), 601–616. https://doi.org/10.5277/ppmp170147.
Sajidu, S., Henry, E., Kwamdera, G., Mataka, L., 2005. Removal of lead, iron and cadmium ions by means of polyelectrolytes of the Moringa oleifera whole seed kernel. WIT Transactions on Ecology and the Environment 80, 251–258.
Saleem, M., Bachmann, R.T., 2019. A contemporary review on plant-based coagulants for applications in water treatment. Journal of Industrial and Engineering Chemistry 72, 281–297. https://doi.org/10.1016/j.jiec.2018.12.029.
Salih, I.E., Tahir Hüsunet, M., Basri Ila, H., 2019. Cell Division, Cytotoxicity, and the Assays Used in the Detection of Cytotoxicity. Cytotoxicity - Definition, Identification, and Cytotoxic Compounds 1–19. https://doi.org/10.5772/intechopen.88368.
Sanghi, R., Bhatttacharya, B., Singh, V., 2002. Cassia angustifolia seed gum as an effective natural coagulant for decolourisation of dye solutions. Green Chemistry 4 (3), 252–254. https://doi.org/10.1039/b200067a.
Sanmugapriyaa, E., Venkataraman, S., 2006. Toxicological investigations on Strychnos potatorum Linn seeds in experimental animal models. Journal of Health Science 52 (4), 339–343. https://doi.org/10.1248/jhs.52.339.
Sapana, M.M., Sonal, C.G., Raut, D.P., 2012. Use of Moringa Oleifera (Drumstick) seed as Natural Absorbent and an Antimicrobial agent for Ground water Treatment. Research Journal of Recent Sciences Res.J.Recent Sci 1 (3), 31–40.
Saranya, P., Ramesh, S.T., Gandhimathi, R., 2014. Effectiveness of natural coagulants from non-plant-based sources for water and wastewater treatment—a review. Desalination and Water Treatment 52 (31–33), 6030–6039. https://doi.org/10.1080/19443994.2013.812993.
Saranya, P., Ramesh, S.T., Gandhimathi, R., 2022. Coagulation performance evaluation of alginate as a natural coagulant for the treatment of turbid water. Water Practice and Technology 17 (1), 395–404. https://doi.org/10.2166/wpt.2021.123.
Saulawa, S.B., Okuofu, C.A., Ismail, A., Otun, J.A., Adie, D.B., Yakasai, I.A., 2011. Effect of deterioration on the turbidity removal potentials of Moringa oleifera seed extract. In: 7th Annual National Conference of the Society for Occupational Safety and Environmental Health (SOSEH), p. 9.
Sciban, M., Klasnja, M., Stojimirovic, J., 2005. Investigation of coagulation activity of natural coagulants from seeds of different leguminose species. Acta Periodica Technologica 266 (36), 81–90. https://doi.org/10.2298/apt0536081s.
Seetha, D. S., Raju, R., Rao, V. N., Prasad, P. R., & Babu, N. C. (2012). Sorption Of Lead (II) Ions from wastewater using Carica Papaya leaf powder. 6, 1577–1581.
Sellami, M., Zarai, Z., Khadhraoui, M., & Jdidi, N. (2014). Cactus juice as bio fl occulant in the coagulation – fl occulation process for industrial wastewater treatment: a comparative study with polyacrylamide Roland Leduc and Faouzi Ben Rebah. 1175–1181. doi:10.2166/wst.2014.328.
Sergeev, A. (2015). Flora of Qatar. Chick pea (Cicer arietinum) seeds, light tan Kabuli variety, in spice section in Souq Waqif (Old Market). Doha, Qatar, September 11, 2015. https://www.asergeev.com/pictures/archives/compress/2015/1649/07.htm.
Shan, T.C., Matar, M.Al, Makky, E.A., Ali, E.N, 2017. The use of Moringa oleifera seed as a natural coagulant for wastewater treatment and heavy metals removal. Applied Water Science 7 (3), 1369–1376. https://doi.org/10.1007/s13201-016-0499-8.
Sharma, S., Bhattacharya, A., 2017. Drinking water contamination and treatment techniques. Applied Water Science 7 (3), 1043–1067. https://doi.org/10.1007/s13201-016-0455-7.
Shewry, P.R., Napier, J.A., Tatham, A.S., 1995. Seed storage proteins: Structures and biosynthesis. Plant Cell 7 (7), 945–956. https://doi.org/10.1105/tpc.7.7.945.
Shojaemehr, M., Alamholo, M., Soltani, J., 2020. Investigation of antibacterial and antioxidant activity of Citrus medica L extract on human pathogenic bacteria. Avicenna Journal of Clinical Microbiology and Infection 7 (1), 8–14.
Sillanpää, M., Ncibi, M.C., Matilainen, A., Vepsäläinen, M., 2018. Removal of natural organic matter in drinking water treatment by coagulation: A comprehensive review. Chemosphere 190, 54–71. https://doi.org/10.1016/j.chemosphere.2017.09.113.
Skotta, A., Jmiai, A., Elhayaoui, W., El-asri, A., Tamimi, M., Assabbane, A., Issami, S.El., 2023. Journal of the Taiwan Institute of Chemical Engineers Suspended matter and heavy metals (Cu and Zn) removal from water by coagulation /flocculation process using a new Bio-flocculant: Lepidium sativum. Journal of the Taiwan Institute of Chemical Engineers 145 (December 2022), 104792. https://doi.org/10.1016/j.jtice.2023.104792.
Solanki, Y.S., Agarwal, M., Gupta, A.B., 2022. Development of an integrating coagulation and reverse osmosis system to treat highly turbid water using synthesized coagulants. Water Science and Technology 85 (2), 562–577. https://doi.org/10.2166/wst.2022.001.
Soros, A., Amburgey, J.E., Stauber, C.E., Sobsey, M.D., Casanova, L.M., 2019. Turbidity reduction in drinking water by coagulation-flocculation with chitosan polymers. Journal of Water and Health 17 (2), 204–218. https://doi.org/10.2166/wh.2019.114.
Subramanium, S., Nand, V., Maata, M., Koshy, K., 2011. Moringa oleifera and other local seeds in water purification in developing countries. Research Journal of Chemistry and Environment 15 (2), 135–138.
Taiwo, A.S., Adenike, K., Aderonke, O., 2020. Efficacy of a natural coagulant protein from Moringa oleifera (Lam) seeds in treatment of Opa reservoir water, Ile-Ife, Nigeria. Heliyon 6 (1), e03335. https://doi.org/10.1016/j.heliyon.2020.e03335.
Teh, C.Y., Budiman, P.M., Shak, K.P.Y., Wu, T.Y., 2016. Recent Advancement of Coagulation-Flocculation and Its Application in Wastewater Treatment. Industrial and Engineering Chemistry Research 55 (16), 4363–4389. https://doi.org/10.1021/acs.iecr.5b04703.
Tetteh, E.K., Rathilal, S., 2020. Application of Organic Coagulants in Water and Wastewater Treatment. Organic Polymers 1–18. https://doi.org/10.5772/intechopen.84556.
Tetteh, E.K., Rathilal, S., Robinson, K., 2017. Treatment of industrial mineral oil wastewater – effects of coagulant type and dosage. Water Practice and Technology 12 (1), 139–145. https://doi.org/10.2166/wpt.2017.021.

Thakur, Kumar, R., Chaudhari, P., Shankar, R, 2021. Removal of Heavy Metals Using Bentonite Clay and Inorganic Coagulants. Removal of Emerging Contaminants Through Microbial Processes 47–69. https://doi.org/10.1007/978-981-15-5901-3_3.
Thirugnanasambandham, K., Karri, R.R., 2021. Preparation and characterization of Azadirachta indica A. Juss. plant based natural coagulant for the application of urban sewage treatment: Modelling and cost assessment. Environmental Technology and Innovation 23, 101733. https://doi.org/10.1016/j.eti.2021.101733.
Tie, J., Zheng, Z., Li, G., Geng, N., Chang, G., Yu, L., Ji, Y., Shi, L., Chang, Y., Hu, L., 2019. Removal of an anionic azo dye direct black 19 from water using white mustard seed (Semen sinapis) protein as a natural coagulant. Journal of Water Reuse and Desalination 9 (4), 442–451. https://doi.org/10.2166/wrd.2019.018.
Tripathy, A.K., Mahalik, S., Sarangi, C.K., Tripathy, B.C., Sanjay, K., Bhattacharya, I.N., 2019. A pyro-hydrometallurgical process for the recovery of alumina from waste aluminium dross. Minerals Engineering 137 (October 2018), 181–186. https://doi.org/10.1016/j.mineng.2019.04.009.
Tsamo, C., Zama, E. F., Yerima, N. E., Nelson, A., & Fuh, M. (2021). Comparing the Coagulation Performance of Rice Husk, Cypress Leaves, and Eucalyptus Leaves Powders with That of Alum in Improving the Turbidity and pH of Some Local Water Sources in Bamenda, Cameroon. 2021.
UNEP. (2016). A Snapshot of the World's Water Quality: Towards a Global Assessment.
UNICEF/WHO. (2021). Progress on Household Drinking Water. 2000-2020. Five years into the SDGs.
Unnisa, S.A., Bi, S.Z., 2018. Carica papaya seeds effectiveness as coagulant and solar disinfection in removal of turbidity and coliforms. Applied Water Science 8 (6), 1–8. https://doi.org/10.1007/s13201-018-0791-x.
Varkey, A.J., 2020. Purification of river water using Moringa Oleifera seed and copper for point-of-use household application. Scientific African 8. https://doi.org/10.1016/j.sciaf.2020.e00364.
Vega, A.P., Palanca, C.F., de Oliveira, M.A.C., Ito, C.Y.K., dos Reis, A.G., 2021. Use of Moringa oleifera seed as a natural coagulant in domestic wastewater tertiary treatment: Physicochemical, cytotoxicity and bacterial load evaluation. Journal of Water Process Engineering 40 (October 2020). https://doi.org/10.1016/j.jwpe.2020.101859.
Vijayaraghavan, G., Sivakumar, T., Kumar, V., 2011. Application of Plant Based Coagulants for Waste Water Treatment. International Journal of Advanced Engineering Research and Studies 1 (1), 88–92.
Vishali, S., Karthikeyan, R., 2015. Cactus opuntia (ficus-indica): an eco-friendly alternative coagulant in the treatment of paint effluent. Desalination and Water Treatment 56 (6), 1489–1497. https://doi.org/10.1080/19443994.2014.945487.
Vunain, E., Masoamphambe, E.F., Mpeketula, P.M.G., Monjerezi, M., Etale, A., 2019. Evaluation of coagulating efficiency and water borne pathogens reduction capacity of Moringa oleifera seed powder for treatment of domestic wastewater from Zomba, Malawi. Journal of Environmental Chemical Engineering 7 (3). https://doi.org/10.1016/j.jece.2019.103118.
Wei, H., Gao, B., Ren, J., Li, A., Yang, H., 2018. Coagulation/flocculation in dewatering of sludge: a review. Water Research 143, 608–631.
WHO. (2006). Guidelines for Drinking-water Quality First Addendum To Third Edition Volume 1 Recommendations. 1. http://apps.who.int/iris/handle/10665/43428.
WHO. (2017). Guidelines for Drinking-water Quality. doi:10.5005/jp/books/11431_8.
WHO. (2019). Compendium of WHO and other UN guidance on health and environment. https://www.who.int/tools/compendium-on-health-and-environment/wash.
Wilson, L.D., 2014. An Overview of Coagulation-Flocculation Technology. Water Conditioning & Purification International Magazine.
World Bank. (2021). Water Overview: Development news, research, data. https://www.worldbank.org/en/topic/water/overview.
Yimer, A., Dame, B., 2021. Papaya seed extract as coagulant for potable water treatment in the case of Tulte River for the community of Yekuset district, Ethiopia. Environmental Challenges 4. https://doi.org/10.1016/j.envc.2021.100198.
Zainol, N.A., Bakar, S.N.S., Zailani, S.N., Ghani, A.A., Ahmad Sohaimi, K.S., 2020. Surface Water Treatment with Natural Starches as Coagulant via Coagulation Process. IOP Conference Series: Materials Science and Engineering 932 (1). https://doi.org/10.1088/1757-899X/932/1/012048.
Zand, A.D., Hoveidi, H., 2015. Comparing aluminium sulfate and poly-aluminium chloride (PAC) performance in turbidity removal from synthetic water. Journal of Applied Biotechnology Reports 2 (3), 287–292.
Zhao, Z., 2020. Effects of drinking water treatment processes on removal of algal matter and subsequent water quality. The University of Western Ontario (Canada.
Zhu, Z., Dou, J., 2021. An extended entropic model for cohesive sediment flocculation in a piecewise varied shear environment. Entropy 23 (10), 1263.