Application of Natural Coagulants in Water Treatment

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The most popular and conventional method for water treatment (WT) is the use of chemical-based coagulants including ferric chloride ($FeCl_3$), alum ($AlCl_3$), synthetic polymers (polyacrylamide), and poly aluminum. However, the use of this approach is not sustainable as it leads to the production of a large volume of non-biodegradable sludge. Natural coagulants, on the other hand, serve as an alternative sustainable strategy for the removal of turbidity and WT, as they are cheap, safe, and biodegradable. Natural coagulants are derived from three major sources, which include plants, animals, and microorganisms.

Keywords: biodegradable ; sustainable ; cost-effective ; eco-friendly

1. Water Treatment Using Chemical Coagulants

The application of chemicals in removing colloidal impurities in water is referred to as chemical coagulation, whereas flocculation is the formation of flocs as a result of neutralizing the charge [1]. The most popular and generally used chemical coagulant in WT is 'alum', of which the chemical formula is KAl $(SO4)_2 \cdot 12H_2O$ and the chemical name is potassium aluminum sulphate. At a pH of 8.0 and a concentration of 450 mgL^{-1}, alum eliminates 99% of the color from the turbid and water [2]. When combined with other coagulants, alum's potency increases. For instance, when aluminum sulphate was combined with poly ferric sulphate (PFS) and polyacrylamide (PAA), the chemical oxygen demand (COD) removal efficiency increased from 68% to 82% [3][4]. In a previous study, ferric chloride/iron (III) chloride at a pH of 6.0 was used as a coagulant to reduce the COD levels of water from the cosmetic industry by 63.9% [5]. Ferric chloride was also used to treat water from molasses and was reported to reduce the color and COD by 96% and 86%, respectively [6]. Chemical coagulants are effective at minimizing the chemical and biochemical oxygen demand, as well as oil and grease [7][8]. In another study, for the treatment of black liquor water, several chemical coagulants including aluminum chloride, poly-aluminum chloride, and anionic PAA (polyacrylamide) were used. The composite could eliminate 95% of total dissolved solids (TDS), 88% of the color, and 80% of COD [9]. These methods utilize additives (chemicals) to segregate small-sized particles in large flocs prior to their removal via sedimentation [10][11]. Poly-aluminum chloride and poly-titanium chloride can reduce the water turbidity from 7.0 NTU to 1.2 NTU [12][13][14][15]. Poly-aluminum ferric chloride at a 5mg/L concentration and pH of 7.5 can eliminate the color and turbidity from water by 86 and 100%, respectively, at pH of 7.5. Similarly, water turbidity can be reduced from 9 NTU to less than 1.0 NTU in a short span of 15 min using polymeric zinc-iron-phosphate [16][17].

Thus, chemical coagulants have a number of benefits as they are easily obtainable and can operate over a broad pH spectrum. They can be used alongside additives for long-term storage and increased efficiency. Other benefits include higher efficiency at low concentrations, easy water dissolvability, and the removal of turbidity and microorganisms such as *E. coli* by 99%. However, it is also true that the use of chemical coagulants jeopardizes the environment and human health. They are known to persist in water until the coagulation process is over, are not biodegradable, and, as a result, treated water contains traces of these chemicals [18][19], which leads to various neurological disorders including Alzheimer's disease [20][21][22], dementia, encephalopathy, and Hippocampal neuron staining. Aluminum traces may cause diseases such as Down's syndrome and Parkinson's disease, convulsions, and even death [23][24]. Moreover, high operational costs, the large quantity of sludge, and the cost of disposal are some of the limitations of chemical coagulants [25].

2. Emerging Use of Natural Coagulants

Considering the global issues related to chemical WT (being expensive, toxicity to humans and the environment, corrosive and carcinogenic nature, altering the pH of treated water, producing hazardous and non-biodegradable sludge, high disposal costs, etc.) [26][27][28], there is a need to explore other possible measures so as to reduce the ill effects of such coagulants on the ecosystem [29][30][31]. Thus, there has been a recent paradigm shift in water and WT, which encouraged industries to improve the culture of water operators in adopting and implementing sustainable development in their activities. Among functional practices is the replacement of chemicals with natural substances in WT processes, which has led to decreased environmental effects in terms of production, consumption, and secondary waste management. Natural coagulants are polyelectrolytes, which can be anionic, cationic, or neutral polymers [32]. They are safe and cost-effective with a great capacity to maintain the pH of the water being treated. Unlike chemical coagulants, natural coagulants do not increase the metal load during treatment and are characterized by the generation of a low volume of sludge, thereby making the cost of disposal very low [33][34], due to which they are a sustainable alternative to chemicals. Earlier research proved the effectiveness of natural coagulants in WT applications [32][35][36][37][38].

2.1. Sustainability of Natural Coagulants

Sustainability is the mode of development that fulfills the needs of current and future generations [39]. Although the crucial factor in the treatment of water is performance efficiency, the reliability of technology is also essential as per the concept of sustainability asserted by the United Nations. Thus, the concept of sustainability involves a combination of social, environmental, and financial aspects [40].

The social aspect of the sustainability of natural coagulants involves industrial acceptance and public health improvement. Industrial acceptance encompasses the ability of natural coagulants to provide results similar to chemical coagulants and be used as an alternative. However, due to the lack of real or pilot-scale use of plant-based coagulants and the lack of approval and regulatory guidelines in the treatment of potable water, industries hesitate to adopt natural coagulants. WT using natural coagulants, especially in rural areas, may facilitate health and hygiene and improve the living standards of all individuals (**Figure 1**). The technical aspect of sustainability involves treatment efficiency, product stability, availability of materials, and compatibility with other techniques. Several natural coagulants have been time-tested and proven to be very efficient in the treatment of water and wastewater. Due to their natural origin, natural coagulants are considered safe and non-toxic. However, the toxicity of organic coagulants in humans and the environment still remains unclear, and there is a need to confirm their environmental safety. Thus, meticulous selection and dose optimization of efficient natural coagulants could provide promising results in WT and may act as a substitute for chemical coagulants. As discussed previously, natural coagulants offer reliability and robustness, are easily available, and can be obtained from a wide range of sources such as plants, microorganisms, or animals [37][41][42]. However, their susceptibility to biodegradation by microbial or other environmental factors adversely affects their long-term storage (shelf-life) and commercialization [43][44]. Environmental sustainability criteria involve the utilization of biodegradable and plant-based coagulants that are eco-friendly and capable of generating biodegradable sludge [45], which can be used for several other purposes such as agricultural practices, landfills, and in civil engineering industries [46][47].

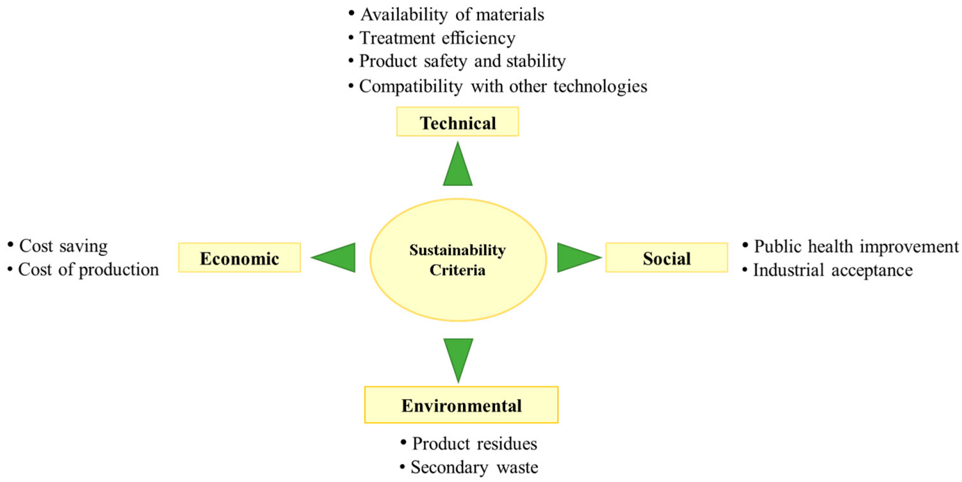

Figure 1. Sustainability criteria of natural coagulants.

The economic aspect of sustainability involves the use of cost-effective coagulants for WT. However, this claim is dissatisfactory as it does not address several other factors such as the cost of processing and maintenance or the variation due to geographical regions. Hence, the cost advantage of natural coagulants over chemical coagulants has not been well addressed. Therefore, one efficient strategy to increase the economic sustainability of natural coagulants is to use a combination of coagulants in order to compensate for the procurement cost and consumption demand along with the synergistic increase in clean-up efficiency [48]. Hybridizing natural coagulants with other coagulants to lower their utilization cost is an additional method to enhance the economics of WT. In contrast, the use of versatile natural coagulants may also result in a reduction in overall costs because many treatment functions can be carried out with a single substance in a single treatment unit. Moreover, as the majority of stated claims were based on lab-scale experimentation, it is challenging to translate the advantages of employing natural coagulants, such as the ‘creation of fewer sludge’ and ‘no need for pH adjustment’ into economic benefits. The ‘cost-effectiveness’ that is tangentially related to the advantages of employing natural coagulants must be more thoroughly evaluated in pilot studies. Because there has not been a thorough analysis of the total expenses of the coagulation process from extraction to the effects on other treatment units, the researchers cannot draw conclusions on the economic aspect of natural coagulants [48].

2.2. Plant-Based Coagulants

Coagulants derived from plants are more readily available than those from either animals or microorganisms [36]. There are sufficient reports on the deployment of various plant-based products such as bagasse [49], banana peels [50][51], *Jatropha curcas* L. [52], and *Moringa oleifera* [50] for the treatment of polluted water. Macromolecules including proteins, polysaccharides, and some functional groups are known to promote the process of adsorption, polymer bridging, and charge neutralization [53]. They are usually effective in the treatment of water, with medium turbidity in the range of 50–500 NTU. However, the efficacy of natural coagulants can be enhanced through the optimization of the extraction and purification processes of coagulants [54]. Therefore, the proper extraction process using plant-based materials can exhibit better performance in the coagulation process, leading to greater/higher waste removal efficiency.

Some of the most widely used plant-based coagulants include *Moringa oleifera* Lam. (seeds), *Cicer arietinum* L. (seeds), *Azadiracta indica* A. Juss. (leaves), *Cactus latifolia* L.(leaves), *Pisum sativum* L. (seeds), *Vigna mungo* L. (Hepper) (seeds), *Arachis hypogea* L.(seeds), *Zea mays* L. (seeds), *Dolichos lablab* Linn. (fruits), *Phaseolus vulgaris* L. (seeds), etc. [55][56][57]. In addition to these, seeds of nirmali are also the source of anionic polyelectrolytes, and their carboxylic acid (–COOH) and hydroxyl (–OH) groups boost the effectiveness of coagulation. Galactomannan and galactan, polysaccharides from the seeds of *Strychno spotatorum* L.fil., are potent enough to decrease water turbidity by 80%. Moreover, plants such as Acacia, Catenae, and Schinopsis can also be used to remove contaminants from water as they possess naturally occurring tannins [58]. Species of cactus such as *Opuntia latifaria* L. are also used as natural coagulants as they contain certain compounds, such as d-galactose, d-rhamanosei, d-xylose, l-arabinose, and galacturonic acid, which are responsible for the bridging action with contaminants in water during the coagulation process [59]. The fruit of *Prunus armeniaca* L. has also been reported for its use as a purifying agent in ancient periods in countries such as Egypt and China, historically dating back to the 1100s [60]. The form of natural coagulants used in the coagulation process can also influence turbidity removal efficiency. For example, when the seeds of *Tamarindus indica* L. were blended in water [61], it was more effective than the water extract derived from ground seeds [62]. In addition to turbidity removal, the common bacteria present in surface water (e.g., *Escherichia coli*) can also be eliminated [63]. The wastes of many fruits possess coagulation properties, whereas some exhibit antimicrobial activity due to the presence of saponins, phenols, and flavonoids [63][64][65]. It was reported by [66] and [67] that the colloids present in the leaves of *H. undatus* Haw. resemble those present in the seeds of *M. oleifera* Lam. and are cationic in nature. The processes of colloid adsorption and neutralization of the charge are considered feasible means of coagulation, which results in the formation of flocs. **Table 1** summarizes the reports on the use of natural coagulants in WT and their relative pollutant removal efficiency.

Table 1. Plant-based natural coagulants used in the treatment of polluted water.

Coagulant	Part Used	State of Coagulant	Opt. Dosage	Removal Efficiency (%)	References
***M.oleifera* Lam. (Drumstick)**	**Seeds**	**Powder**	**0.2 gL^{-1}**	**Turbidity removal (61.60%); COD removal (65.00%)**	[68]
***M.oleifera* Lam. (Drumstick)**	**Seeds**	**Deoiled powder**	**6000 mgL^{-1}**	**TSS removal (95%)**	[69]
***M.oleifera* Lam. (Drumstick)**	**Seeds**	**Powder**	**500 mgL^{-1}**	**Turbidity removal (96.80%)**	[70]
***M.oleifera* Lam. (Drumstick)**	**Seeds**	**Powder**	**0.6 gL^{-1}**	**Turbidity removal (82%), COD removal (83%)**	[71]
***M. oleifera* Lam. (Drumstick)**	**Seeds**	**Stock solution**	**0.3 mgL^{-1}**	**Cu and Cd removal (98%); Pb removal (78%)**	[72]
***M.oleifera* Lam. (Drumstick) and alum**	**Seeds**	**Solution**	**70 and 80 mgL^{-1}**	**COD removal (50.41%); Turbidity removal (86.14%); TSS removal (81.52%)**	[73]
***M.oleifera* Lam. (Drumstick) and alum**	**Seeds**	**Stock solution**	**50 mgL^{-1} each**	**BOD removal (80.67%); COD removal (66.73%)**	[74]

Coagulant	Part Used	State of Coagulant	Opt. Dosage	Removal Efficiency (%)	References
M.oleifera Lam. (Drumstick) *Cicer arietinum* L. (Chickpea)	Seeds	Powder	50 mgL^{-1}	Turbidity removal *M. oleifera* (82.2%); Chickpea (81.2%); Cactus (78.54%)	[75]
M. oleifera Lam. (Drumstick) and *Musa acuminate* L. (Banana peel)	Seeds	Powder	200 and 400 mgL^{-1}	Pb removal (81%); Ni removal (74%); Cd removal (97%)	[76]
Malus sylvestris L. (European crab apple) and aluminum sulphate	Seeds	Stock solution	62.5 mgL^{-1}	Turbidity removal (66%)	[77]
Cyamopsis tetragonoloba L. (Taub.) (Guar)	Gum	Powder	300 mgL^{-1}	Turbidity removal (67.82%)	[77]
P.ovata (Psyllium) and PAC	Husk	Powder	0.4 and 7.2 gL^{-1}	Color removal (90%); COD removal (96%)	[78]
Parkia biglobosa Jacq. (Locust bean)	Gum	Powder	300 mgL^{-1}	Turbidity removal (67.82%)	[77]
Ocimum basilicum L. (Basil plant)	Seeds	Stock solution	1.6 mgL^{-1}	Color removal (68.50%); COD removal (61.60%)	[79]
Opuntia ficus Linn. (Miller) (Cactus)	Mucilage	Powder	150 mgL^{-1}	Turbidity removal (49.56%)	[77]
Plantago major Linn. (Carls) (Broadleaf plantain)	Mucilage	Powder	297.6 mgL^{-1}	Color removal (92.4%); COD removal (81.60%)	[80]
Hibiscus rosasinensis Linn. (Carls) (China rose) and alum	Seeds	Powder	500 and 400 mgL^{-1}	Turbidity removal; Hibiscus (60%); Alum (100%)	[81]
Trigonella foenum L. (Fenugreek)	Seeds	Powder	0.1 gL^{-1}	Turbidity removal (58%); COD removal (63%)	[68]
Abelmoschus esculentus L. (Okra)	Mucilage	Powder	3.2 mgL^{-1}	Turbidity removal (97.24%); COD removal (85.69%)	[82]
Abelmoschus esculentus L. (Okra) and Iron (III) chloride hexa hydrate	Mucilage	Stock solution	2.5 mgL^{-1}	Turbidity removal (74%)	[77]
Cicer arietinum L. (Chickpea)	Seeds	Powder	2 gL^{-1}	TDS removal (82%); COD removal (84%); BOD removal (83%)	[83]
Cicer arietinum L. (Chickpea)	Seeds	Powder	0.1 gL^{-1}	Turbidity removal (78.33%); COD removal (83%)	[68]
Dolichos lablab Linn (Hyacinth bean)	Fruits	Powder	0.2 gL^{-1}	Turbidity removal (71.74%); COD removal (75%)	[68]
Tamarindus indica L. (Tamarind)	Seed	Powder	400 mgL^{-1}	Turbidity removal (97,72%)	[84]
Hibiscus sabdariffa L. (Roselle)	Seed	Powder	60 mgL^{-1}	Turbidity removal (87.18%)	[85]
Opuntia indica L. (Mill.) (Cactus)	Mucilage	Powder	0.4 gL^{-1}	Turbidity removal (78.54%); COD removal (75%)	[74]
Momordica charantia L. (Bitter gourd)	Seed	Solution	400 ppm	Turbidity removal (61.03%)	[86]
Gossypium barbadense L. (Cotton)	Seed	Oil	30 mLL^{-1}	TSS removal (66.27%)	[87]
Ricinus communis L. (Castor)	Seed	Oil	40 mLL^{-1}	TSS removal (66.67%)	[83]
S.potatorum L. f.(Nirmali)	Seed	Stock solution	60 mLL^{-1}	BOD removal (65.23%), COD removal (72.71%), Turbidity removal (75.20%)	[87]
Musa acuminate L. (Banana)	Peel	Juice	90 mLL^{-1}	Turbidity removal (98.50%)	[88]

Coagulant	Part Used	State of Coagulant	Opt. Dosage	Removal Efficiency (%)	References
Zea mays **L. (Maize)**	**Seed**	**Powder**	**30 gL^{-1}**	**COD removal (68.82%); Color removal (47.03%)**	**[89]**
Plantago ovata **Forssk(Isabgol)**	**Seed**	**Powder**	**1.5 mgL^{-1}**	**COD removal (89.30%)**	**[90]**
P.vulgaris **Gustav Hauser (French bean)**	**Seed**	**Powder**	**1.5 mgL^{-1}**	**Color removal (73%)**	**[91]**
Cassia fistula **L. (Golden shower)**	**Seed**	**Powder**	**0.5 gL^{-1}**	**Color removal (71.3%)**	**[92]**
Vitis vinifera **L. (Grape vine)**	**Seed**	**Powder**	**1.5 mgL^{-1}**	**Color removal (80%)**	**[93]**
Citrus sinensis **L. (Osbeck) (Orange)**	**Peel**	**Powder**	**0.2 gL^{-1}**	**Turbidity removal (97%)**	**[94]**
Artocarpus heterophyllus **Lam. (Jackfruit)**	**Seed**	**Powder**	**60 mgL^{-1}**	**Turbidity removal (43%)**	**[95]**
Jatropha curcas **L. Britton and Mills.(Barbados nut)**	**Seed**	**Powder**	**14 mgL^{-1}**	**Turbidity removal (93%)**	**[96]**
Strychnos potatorum **L. f. (Nirmali)**	**Seed**	**Powder**	**1.5 mgL^{-1}**	**Turbidity removal (90%)**	**[97]**
Carica papaya **Linn. (Papaw)**	**Seed**	**Powder**	**0.4 g per 200 mL**	**Turbidity removal (90%)**	**[98]**
Julifora Prosopis **var. juliflora (Sw.) DC (Mesquite bean)**	**Seed**	**Powder**	**1.5 mgL^{-1}**	**Turbidity removal (96%)**	**[99]**
Acacia mearnsii **De Wild. (Black wattle)**	**Bark**	**Powder**	**14 mgL^{-1}**	**Turbidity removal (75%)**	**[99]**

The most commonly utilized natural coagulants derived from plants are explained below.

2.3. Tannins

Tannin is a polyphenol compound used in the leather industry and is obtained from the wood and bark of trees such as Castanea, Acacia, and Schinopsis [99][100]. The use of tannin extracted from valonia/Asia minor oak has been investigated by several researchers as an effective coagulant in WT [39][40][101][102][103]. They concluded that tannin is a superior alternative to chemical coagulants. Tannin can be used in the removal of dyes such as indigo, azo, triphenylmethanones, and anthraquinonic [104]. The chemical structure of tannins derived from plants and the degree of tannin modification affect their efficiency in water treatment. Tannin contains phenolic groups and is a strong anionic hydrogen donor. The phenolic groups form phenoxide due to rapid deprotonation and are balanced by resonance. It is also considered an amphoteric compound, which not only reduces the turbidity and heavy metals but also the color of water and thus functions as an alternative to chemical coagulants. Thus, it can be concluded that the higher the number of phenolics, the greater the capacity to coagulate will be.

2.4. Nirmali Seeds

Nirmali is a medium-sized tree mainly used as a traditional medicinal plant native to Sri Lanka, southern and central India, and Burma [105]. The seeds of this plant have been reported to have been used over 4000 years ago as a natural coagulant in the treatment of water [106][107]. The majority of research on its usage as a natural coagulant is confined to the Indian sub-continent [62][106][108][109]. Extracts of nirmali seeds are anionic polyelectrolytes that use coagulation (charge neutralization and bridging) for the removal of contaminants in water [110]. It has been observed that the coagulation efficiency can be increased due to the presence of alkaloids, lipids, and carbohydrates containing–COOH and free –OH groups present on the surface. In a previous study, galactomannan and galactan obtained from nirmali seeds reduced the turbidity of a kaolin solution by approximately 80% [111]. The presence of –OH groups, along with galactan and galactomannan chains, is mainly responsible for the water-cleaning property.

2.5. Moringa Seeds

Moringa oleifera Lam. (horseradish or drumstick tree) is a versatile, medium-sized tree that usually grows in semi-arid, tropical, or sub-tropical areas and in various parts of Africa, Asia, Northwest India, and South America [112] belonging to the Moringaceae family. *M. oleifera* Lam. is non-toxic and is the most frequently identified natural coagulant utilized for WT

[113]. In addition to its use as a source of food, fodder, and medicine, each part of the Moringa plant, including the leaves, seeds, flowers, roots, and bark, can be used as a coagulant for WT [114][115][116]. The seeds of Moringa, in addition to containing edible oil, also contain substances that are soluble in water [117]. Muller et al. [118] and Jahn et al. [119] were among the pioneer researchers who reported the use of *M. oleifera* Lam. seeds for the coagulation process in WT. Muyibi et al. [120] also reported it to be a minimal or low-cost natural coagulant that can be feasibly deployed in WT, at least in rural or semi-urban areas. The work of Ndabigengesere et al. [117], which reported the coagulation property of Moringa seeds in the treatment of water, ignited interest among environmental scientists. The active coagulating agents present in Moringa seeds are reported to be cationic proteins, which are dimeric in nature, possess an isoelectric point between 10 and 11 and a molecular weight of 12–14 kDa, and function via charge neutralization and adsorption mechanisms.

Gassenschmidt et al. [121] also reported that protein is the active ingredient of coagulation in Moringa seeds, possessing a mass of 6.5 kDa and an isoelectric point higher than 10. In a similar report, other researchers [122] stated that the protein has an isoelectric point greater than 9.6 and a mass of 6.5 kDa. In contrast to the aforementioned reports, [123] reported that the coagulating agent is an organic polyelectrolyte rather than a polysaccharide, protein, or lipid, with a molecular mass of 3.0 kDa.

As per the aforementioned reports, the most active coagulating agent is cationic proteins; however, Moringa may contain several other coagulating agents, which need to be studied further. Cationic proteins in the seeds of Moringa work via various electrostatic mechanisms such as neutralization, charge reversal, and adsorption [124]. These bind with impurity particles, which are usually negatively charged. Okuda et al. reported that the coagulation performance of Moringa extracts can be improved by using bivalent cations (Mg^{2+} and Ca^{2+}) [123]. Sulaiman et al. [125] used the seeds of Moringa in WT and observed excellent results. Dotto et al. [126] used the same method in the treatment of textile mill water and a significant COD reduction was reported. For the treatment of water from the dairy industry, seed powder was able to remove ~100% of the turbidity and 99.50–100% of the fecal coliform count. In a similar report, the seed powder could remove ~ 83.63% of the turbidity from laundry water [127]. Hence, *M. oleifera* is among the most versatile and reliable natural coagulants and has been proven to be a promising sustainable alternative to chemical coagulants.

2.6. Chickpea Seeds

Cicer arietinum L. (Fabaceae), commonly known as chickpea, is an important pulse crop that is grown in arid and semi-arid zones with good soil moisture and adequate rainfall. Hiremath et al. [128] and Jaseela et al. [129] used chickpea seeds to treat water released from the dairy industry and reported the removal of turbidity of 86.29%. Another group reported a more than 95% reduction of preliminary turbidity, which was similar to that of alum [130]. Choy et al. (2015) reported that the presence of high sugar and protein contents in chickpea were mainly responsible for the removal/coagulation of particles [36].

2.7. Peanut Seeds

The seeds of *Arachis hypogea* L. (peanut) are an important source of protein and are well known for their high lipid content. Traditionally, the seeds have been used against inflammation while the seed oil has been used as an ointment [131]. The lipid part of the peanut constitutes approximately half of its dry weight, but the lipid does not contribute to its purification properties. As a result, the relative percentage of the active agent is markedly decreased, leading to lower efficiency in the removal of raw surface-water turbidity. Mataka et al. [132] reported that peanut seeds exhibit a similar effect as that of moringa seeds, and delipidated cakes were found to be more effective (in the removal of heavy metals from wastewater) than the crude seed extract. Therefore, the effectiveness of peanut coagulation activity can be increased by removing the lipidic portion from the seeds.

2.8. Soybean Seeds

The seed extracts of *Glycine max* L. (soybean) can be used as the main coagulant or a coagulant aid to alum for cleaning contaminated raw surface water [133][134]. The coagulation efficiency of soybean seeds was excellent in the clarification of surface water beyond 450 NTU, whereas, as a coagulant aid to alum, ~96% turbidity removal was reported [134]. Although soybean seeds have a large lipid fraction that is considered second to groundnut, the lipid part does not contribute to coagulation activities. Therefore, seed delipidation (the removal of lipids) improves the coagulation potential. Moreover, deoiled seeds of soybeans have been reported to be less expensive bioadsorbents for the treatment of water contaminated by different dyes [37][135][136]. Soybean seeds possess palmitic acid, whereas stearic acid found in *Hibiscus esculentus* has been associated with bactericidal activities. Thus, their extracts have potential anti-bacterial properties and can treat raw surface water [131][137].

2.9. Cacti Mucilage

Opuntia ficus indica (OFI) (L.) *P. Mill* is the most common species of cactus, which has been used mainly for its medicinal properties and as a dietary source, as well as for treating water. *Cactus latifaria* has also been used as an organic coagulant [98]. Opuntia possesses a high coagulation capacity due to the presence of mucilage, which is a complex carbohydrate, and, hence, it is used as a potential coagulant for treating water [138][139]. Thus, it is eco-friendly and can be used as an alternative to aluminum and iron salts due to its abundance, renewability, adaptability, and biodegradability [5]. Rebah et al. also reported the potential of Opuntia in the treatment of wastewater [140]. Opuntia's mucilage has different sugar molecules including d-galactose, d-xylose, l-rhamnose, l-arabinose, and galacturonic acid [138]. However, the most active coagulating agent is galacturonic acid [141], which contributes to the removal of 50% turbidity. Galacturonic acid may also exist in a polymeric form as polygalacturonic acid. It is anionic due to the presence of carboxylic functional groups, which undergo partial deprotonation in an aqueous solution [142]. The mucilage in Opuntia species functions mainly via adsorption and the bridging coagulation process in which dirt particles bind to the mucilage and facilitates the removal of turbidity.

2.10. Okra Seed Extract

The coagulation potential of okra (*Abelmoschus esculentus* (L.) Moench) seed extracts has been examined by [143] who asserted that seeds extracted using distilled water and a sodium chloride solution can be used as organic coagulants for the removal of turbidity from water with an efficiency of 54.5% and 92% for distilled water and a NaCl (1.0 N) solution, respectively. Raji et al. [144] discovered that okra seed extracts were very effective in the removal of turbidity from 580 to 5 NTU at a dose of 300 mg/L and pH 7.0, which is within the standard limit recommended by WHO. Similar work conducted by Thakur et al. [145] and Mishra et al. [146] revealed that okra seed extracts can effectively remove dirt from the water even at a dose of 200 mg/L. The work of [122] also shows the effectiveness of okra seed extracts in WT with more than 69% and 95% removal efficiencies for dissolved and suspended solids (from the effluents), respectively.

3. Animal-Based Coagulants

Animals may also act as a crucial source of coagulating agents. They are usually extracted from shellfish exoskeletons, the shells of lobsters, shrimps, insects, crabs, diatoms, and molluscs, and freshwater and marine sponges. Chitosan is a high-molecular-weight biopolymer developed via the deacetylation of chitin. It occurs naturally as a complex sugar (polysaccharide) and is water-loving (hydrophilic), biodegradable, environmentally safe, and capable of absorbing several metal ions efficiently as it contains amino groups in its polymeric chain [147]. The deployment of chitosan as a natural coagulant in the treatment of polluted water in different sectors, including agriculture, textile, detergent, and food industries, as well as paper mills, has been well reported [148][149]. The characteristic feature of chitosan regarding cleaning water is its ability to react and generate a positive charge that destabilizes the negative charge of the colloidal particles [150]. Actinobacteria are also effective in the treatment of contaminated water [151]. Efficient flocculating activity was observed when *Cellulomonas* and *Stretptomyces* spp. were deployed as flocculants in the treatment of kaolin-contaminated water. The substantial effects of these species were shown to be due to the presence of several molecules including proteins, natural sugar, polysaccharides, and uric acid, as indicated by chemical analysis [147]. Chitin is a naturally occurring and the second-most abundant polysaccharide (after cellulose). Every year, at least 10 gigatons of chitin are synthesized and destroyed throughout the biosphere. Chitin is a renewable resource found mainly in complexes with other polysaccharides and proteins. Chitin and its metabolites are utilized as chelating agents in the purification of water by segregating organic substances and heavy metals, as well as in the treatment of sewage via the precipitation of certain anionic wastes and the collection of contaminants such as PCBs (polychlorobenzene). The utilization of 10 mg per liter of chitosan in water has already received approval from the Environmental Protection Agency (EPA) [152].

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