ARTICLE IN PRESS

OPEN ACCESS

Journal of Multidisciplinary Applied Natural Science Vol. xx No. xx (xxxx) https://doi.org/10.47352/jmans.2774-3047.287

Check for updates

Research Article

Alginate as A Natural Coagulant-Aid: Advances, Challenges, and Applications

Hans Kristianto*, Susiana Prasetyo, and Asaf Kleopas Sugih

Received : October 28, 2024 | Revised : May 18, 2025 | Accepted : June 3, 2025 | Online : July 28, 2025

Abstract

Coagulation is a critical step in water and wastewater treatments that is essential for the removal of suspended solids, organic matters, and colloidal particles. Conventional metal-based coagulants such as aluminium sulphate, ferric chloride, and polyaluminium chloride and synthetic polymer such as polyacrylamide are widely used due to their proven efficiency. However, concerns over their environmental impact, including the generation of non-biodegradable sludge, potential health risks, and negative impact on the water ecosystem, have driven the search for alternative, eco-friendly coagulants. Natural coagulants derived from plants, animals, or microorganisms have emerged as promising alternatives, offering advantages like biodegradability, non-toxicity, and lower sludge production. Among these, polysaccharide-based coagulants such as alginate, a biopolymer sourced from brown seaweed and bacteria, have gained significant attention. Alginate's biodegradability, non-toxicity, low cost, and versatile gelation properties make it a potential substitute for synthetic coagulants. This review focuses on the use of alginate as a coagulant-aid, providing an overview of its sources, characteristics, coagulation mechanisms, and variables that affect the coagulation performance. The review also highlights the benefits, challenges, and future research directions for improving the efficiency and scalability of alginate in sustainable water/wastewater treatment processes.

Keywords: alginate, coagulant-aid, sustainability, natural coagulant, wastewater treatment

1. INTRODUCTION

Coagulation is a fundamental step in water and wastewater treatments, playing a crucial role in the removal of suspended solids, organic matters, and colloidal particles that contribute to water turbidity and contamination. Coagulation would induce aggregation of colloid into larger flocs that can be easily separated using sedimentation and filtration. Although other water and wastewater treatment technologies such as adsorption [1][2], membrane filtration [3], advanced oxidation process [4], and biological treatment [5] have been developed and used; coagulation remains a favourable option due to its simplicity and high effectiveness. During coagulation, inorganic metal-based coagulant, both in salt and polymer form, such as aluminium sulphate ($Al_2(SO_4)_3$), ferric chloride ($FeCl_3$), polyaluminium chloride (PAC), and polyferrous sulphate (PFS) is commonly used in water/wastewater treatment due to its high efficiency and proven effectiveness [6]. Other than metal-based coagulants, polymeric synthetic organic flocculants such as polyacrylamide (PAM) and polydiallyldimethylammonium chloride (PDADMAC) are commonly added to improve the coagulation performance.

Although those previously mentioned coagulants are highly effective, there are some drawbacks regarding the environmental impact and health-related concerns [7]. It is known that inorganic coagulants generate a large volume of non-biodegradable sludge that could lead to disposal and health problems, due to its carcinogenic nature. The increase of aluminium content in the treated water is also linked with the possible cause of several degenerative diseases such as dementia and Alzheimer's [8]. Numerous studies have raised concerns about the potential toxicity associated with PAM, PDADMAC, and its derivatives or monomers. Harmful effects on various organisms, including microorganisms [9], freshwater species [10], fish embryos [11], as well as human health [12] and water toxicity [13] have been reported.

Due to these various drawbacks, there is a growing interest in recent years to find more environmentally friendly and sustainable alternative coagulants and coagulant-aids. Natural coagulants, that come from animal, plant, or microorganism

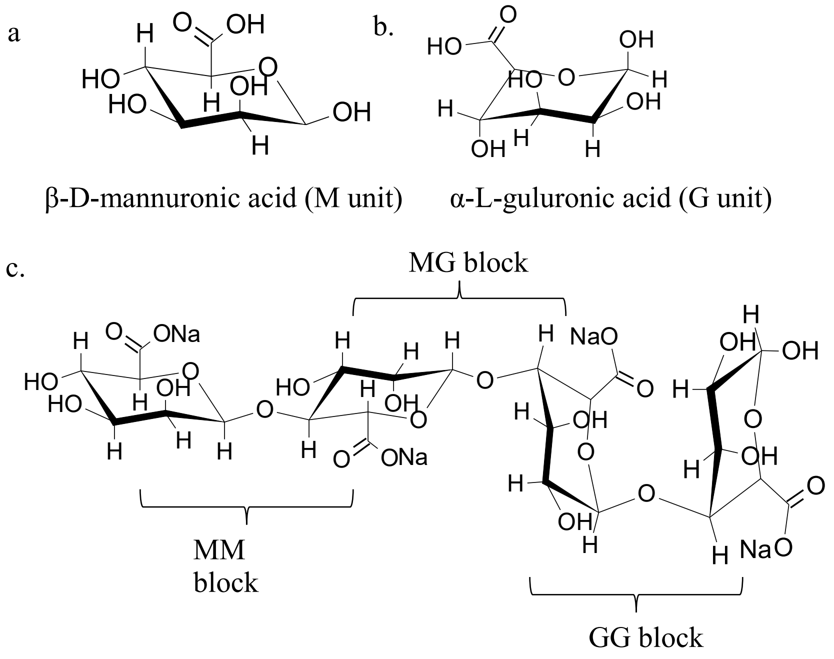

Figure 1. Chemical structure of (a) β-D-mannuronic acid, (b) α-L-guluronic acid, and (c) molecular structure of sodium alginate.

[14], have emerged as a promising alternative to overcome those drawbacks. As it comes from natural resources, natural coagulants offer some advantages such as biodegradability, less toxic, lower coagulant cost, and lower sludge volume production [15]-[17], reducing the environmental burden associated with residual sludge and water contamination. Based on the active coagulating agent, natural coagulants can be classified as proteins, polysaccharides, and polyphenols. Protein-based natural coagulants are typically derived from nuts and legumes and are often applied in their crude extract form as an alternative to inorganic coagulants [18]-[21]. However, a significant challenge persists in its use, particularly in terms of protein extraction and purification, which still needs to be addressed. Conversely, polyphenol-based natural coagulants, with tannic acid as the active coagulating agent, are also commonly utilized [22][23]. However, research in this area remains limited, highlighting the need for further exploration and study. Lastly, polysaccharides, such as starch [24], gum [25], pectin [26][27], and chitosan [28] demonstrate promising potential for use as natural coagulants or coagulant-aids due to its high availability and abundance.

One of the most promising polysaccharides is alginate, typically derived from brown seaweed and several bacteria. Alginate presents numerous advantages, including its biodegradability, non-toxicity, low production cost, and excellent biocompatibility [29]. Its unique gelation properties further enhance its versatility, making it highly suitable for a wide range of applications. These applications span from food additives and packaging materials to tissue engineering, drug delivery systems [29], hydrogels, and composite materials for wastewater treatment [30]. Notably, alginate's combination of eco-friendliness and functional properties makes it a promising alternative of synthetic coagulant-aid and enhancing the efficiency of the coagulation process.

Several review papers regarding the sodium alginate's application in wastewater treatment have been reported in recent years [31]-[37]. Rafiee [34] highlighted various potential applications of alginate in wastewater treatment, especially adsorption of dyes and heavy metals, as well as the combination of alginate and microalgae for pollutant removal. Guo et al. [35] discussed the modification of alginate-based materials (such as hydrogel, aerogel, nanofiber, etc.) with application for antibiotics, dyes, heavy metal ions, and radioactive materials removal from water/ wastewater. Combination of alginate with cellulose [32] and chitosan [33] has also been discussed for their remarkable performance in wastewater treatment. Furthermore, the application of alginate as coagulant or coagooulant-aid has been partly discussed in other review papers [36][38][39]. However, to the best of the authors' knowledge, there is no such paper that provides an in-depth discussion regarding the recent advances of the use of alginate as coagulant-aid in water/wastewater treatment. This review explores the potential sources of alginate and examines its characteristics and properties. It provides a detailed analysis of alginate's coagulation mechanism, supported by a discussion of variables that influence the coagulation performance from recent studies. Furthermore, the review also highlights the benefits, challenges, and prospects of using alginate as a coagulant or coagulant aid, identifying key areas for further investigation.

2. ALGINATE: SOURCE, CHARACTERISTICS, AND PROPERTIES

Alginate is a naturally occurring biopolymer, predominantly extracted from brown seaweed (Phaeophyceae) such as Laminaria, Ascophyllum, and Macrocystis species [40]. It is a polysaccharide composed of repeating units of β-D-mannuronic acid (M unit) and α-L-guluronic acid (G unit) arranged in homopolymeric (MM or GG blocks) or heteropolymeric blocks (MG blocks), as illustrated in Figure 1. Besides seaweed, certain bacterial species like *Pseudomonas* sp. and *Azotobacter* sp., especially *P. aeruginosa* and *A. vinelandii* can also produce alginate as an exopolysaccharide, offering an alternative microbial source [41].

Depending on the source and its production, the molecular weight of alginate might vary between 32,000 to 400,000 g/M [42]. This feature is an important factor that affects the gel formation and viscosity of the gels [43]. The solubility of alginate in water depends on the metal cations bound into the alginate structure. While alginic acid is insoluble in water, the potassium, sodium, and ammonium salt of alginate is are known to be the soluble in water at cold or hot temperature [44], among of these, sodium alginate is commonly used as coagulant aid due to its availability. On the other hand, the presence of divalent and trivalent metal cations, such as Ca^{2+}, Zn^{2+}, Fe^{3+}, and Al^{3+} result in alginate gels via the formation of egg box structure [45]. In this structure, the guluronic acid blocks preferentially bind to the cations, creating a stable gel network. The chemical structure of alginate, particularly the ratio and distribution of M and G blocks, significantly impacts its properties [46]. Alginates rich in G-block tend to form stronger, more rigid gels, while those with higher M-block content produce softer, more elastic gels [47]. The presence of carboxyl groups in the alginate structure [48], as well as the composition of G/M blocks and gelling properties are playing the important role for its application as coagulant/ coagulant-aid.

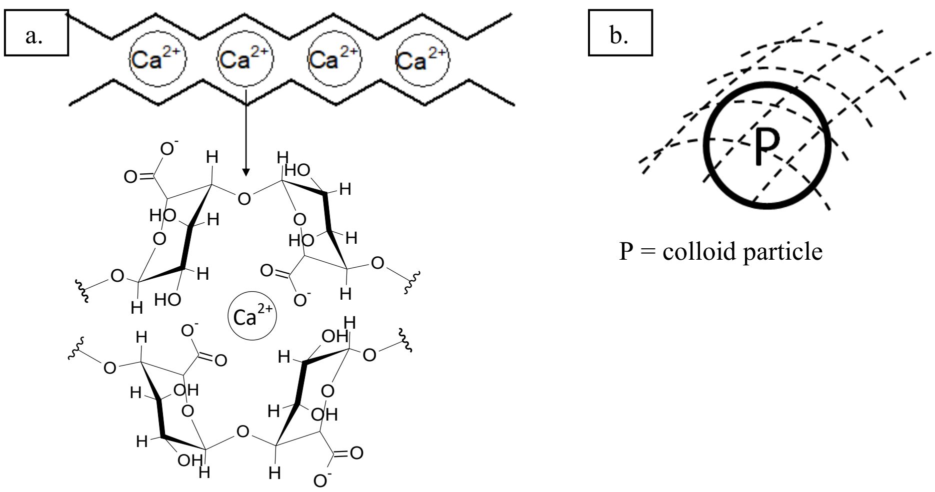

Figure 2. (a) Egg-box structure of calcium ions and alginate (adapted from [54]) and (b) gel network of calcium alginate that trap colloid particle (adapted from [55]).

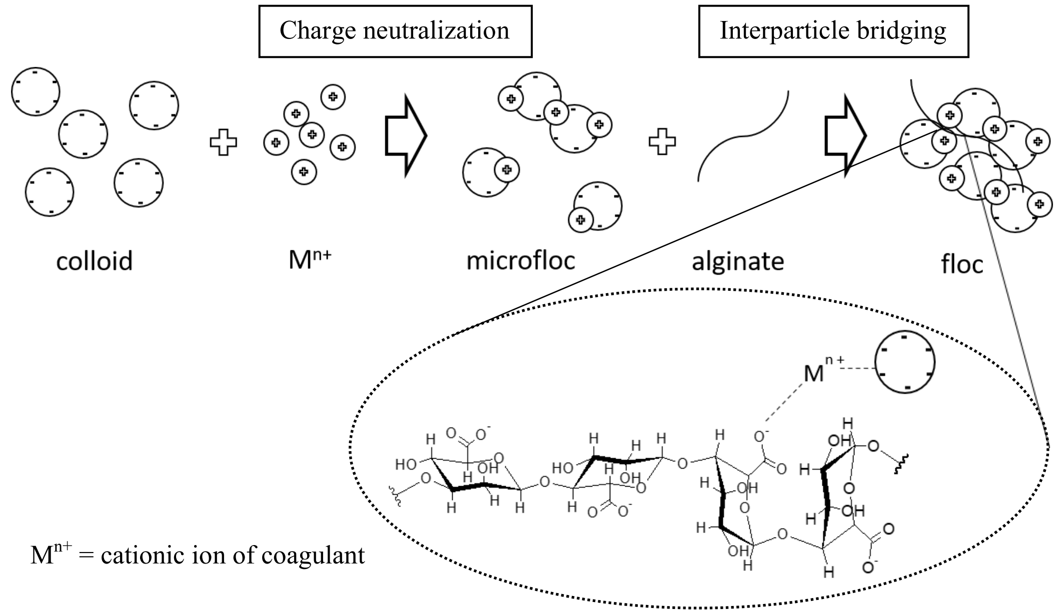

Figure 3. Coagulation mechanism involving alginate as coagulant-aid.

3. SODIUM ALGINATE'S APPLICATION AS COAGULANT-AID

In this section, the coagulation mechanism, the effect of various coagulation variables to the alginate performance as coagulant aid is discussed.

3.1. Coagulation Mechanism

The utilization of calcium ion together with sodium alginate followed the charge neutralization and interparticle bridging mechanism. The positively charged calcium ion can neutralize the negatively charged colloid, which resulted in colloid destabilization via charge neutralization mechanism, as reported in humic acid [49] and microplastic [50] coagulation. The calcium ions need to be added first to make sure the calcium ions interact and reduce the colloid charge [51]. After that, the sodium alginate addition to the colloid system would interact with the calcium ions via G units of the alginate structure, forming the egg-box structure, as illustrated in Figure 2(a). In this stage, the alginate would perform as a bridge between particles, i.e interparticle bridging. On the other hand, there is another opinion regarding the coagulation of calcium alginate via a gel formation that can entrap colloid particles, illustrated in Figure 2(b), and result in floc formation [52]. This mechanism is similar to sweep flocculation of inorganic coagulant, where the colloid particles are entrapped and settled together with hydroxide precipitates such as $Al(OH)_3$ and $Fe(OH)_3$ of inorganic coagulant [53].

As previously mentioned, functioning as coagulant aid, alginate would interact with the positive species in the solution, i.e. the coagulant, as illustrated in Figure 3. Combination of alginate with $Al_2(SO_4)_3$, $FeCl_3$, $TiCl_4$, and PAC has been reported in the literature [56]-[60]. The coagulant would neutralize the negatively charged colloid particles, and then interact with the negative carboxylate functional groups on the alginate structure. The long alginate chain then acts as a particle bridge that aids the coagulation-flocculation process. The order of addition of the coagulant and alginate is also important. The inorganic coagulant needs to be introduced first, followed by the sodium alginate solution. This order will result in a higher coagulation performance and more compacted sludge, compared with addition order in reverse, or in the same time [61].

3.2. Factors Influencing Coagulation Efficiency

There are some important factors that might influence the coagulation performance, namely pH, coagulant dose, colloid concentration, and M/G ratio.

3.2.1. Coagulation pH

The pH of a solution plays a crucial role in influencing the surface charges of both colloidal particles and coagulants, making it a key parameter

Table 1. M and G contents of alginate from several sources.

Source	Species	Mannuronic acid (%)	Guluronic acid (%)	M/G ratio	Reference
Algae	*Bifurcaria bifurcata*	32	68	0.47	[71]-[73]
	Fucus spiralis	48	52	0.92	[71]
	Laminaria digitata	59	41	1.44	[74]
	Sargassum vulgare	56	44	1.27	[75]
Bacteria	*Azotobacter vinelandii*	54	46	1.17	[76]
	Pseudomonas aeruginosa	67–76	24–33	2.03–3.16	[77]
	Pseudomonas mendocina	74	26	2.92	[78]
	Pseudomonas putida	63	37	1.7	[78]

in any coagulation study. The selection of the optimal coagulation pH is essential, as it directly affects the electrostatic interactions between particles and coagulants [62]. Specifically, attention must be paid to the point of zero charge (PZC) of both the colloidal particles and coagulants, so that under the range of pH used, the attractive electrostatic force can be favourably occurred, resulting in the colloid's charge neutralization. Sodium alginate solution is known to have negative zeta potential, a metric that quantify the electrical potential of the colloid's interface and the surrounding fluid [63]. Where at pH 3 to 10, the sodium alginate's zeta potential ranges from -12.5 to -32.5 mV [64]. In systems using sodium alginate as a coagulant aid, the optimal pH is often aligned with the effective pH range of the primary coagulant to maximize the coagulation efficiency [59]. This ensures that sodium alginate enhances the destabilization of colloidal particles, leading to better aggregation and improved water treatment outcomes.

3.2.2. Coagulant Dose and Colloid Concentration

It is known that coagulant dose and colloid concentration in a solution is proportional to each other [65]. At a low coagulant dose, there is insufficient coagulant to effectively neutralize the colloids' charge, resulting in low colloid removal. Conversely, overdosing can result in charge reversal that makes the colloid suspension to re-stabilize [66]. Thus, optimum coagulant dose is needed to obtain the maximum colloid removal [67]. The addition of sodium alginate as coagulant-aid has been reported to decrease the dose of inorganic coagulant. Wu et al. (2012) reported the addition of 1 mg/L sodium alginate with 4.5 mg/L $Al_2(SO_4)_3$ gave similar coagulation performance with $Al_2(SO_4)_3$ only at a dose of 6.5 mg/L [57]. A synergistic effect of sodium alginate with other coagulants such as PAC [59], $FeCl_3$ [68], and $TiCl_4$ [56] has also been previously reported. The presence of sodium alginate as coagulant-aid also positively contributes to floc formation. Combination of $Al_2(SO_4)_3$ and sodium alginate gave a higher growth rate and flocs' size compared to $Al_2(SO_4)_3$ only [56,57], which resulted in lower sludge volume formation [59]. Furthermore, addition of sodium alginate has also improved the floc strength and recovery ability [57]. Overdosing of sodium alginate would result in the decrease of coagulation performance, due to competition between the negatively charged alginate and colloid particles to bind with the positively charged coagulant [59]. Furthermore, overdosing of sodium alginate also resulted in smaller flocs, that resulted from repulsion between micro flocs that hinder formation of bigger aggregate [57]. This phenomenon is similar to other coagulant-aids [25][69][70]. Thus, optimization study to find the best dosing scenario is needed for each different water/wastewater characteristics.

3.2.3. M/G Rasio

Other than two factors above, the composition of alginate also plays an important role during coagulation. According to Moral et al. [54], the G content in the alginate structure plays an important role in the coagulation performance. They demonstrated that low G content (26% G) gave very low coagulation performance due to insufficient binding with calcium ions. Excessive G content (73

–76% G) also decreases the coagulation performance as there is competition with the colloid particles to bind calcium ions, making gels and the precipitate. During this, the alginate cannot be adsorbed onto the particle and lowering the formation of interparticle bridging. It is reported that the best G block content is around 54–56% [54]. The M and G content of alginate from several algae and bacteria is presented in **Table 1**. It can be seen that the M and G content varies between species of algae and bacteria. However the algae's alginate tends to range from 0.47 to 1.44, while bacterial alginate contains lower G content. This knowledge can be useful for choosing the source of alginate for coagulant-aid application.

3.3. Performance of Alginate as Coagulant-aid

Relevant studies that utilized alginate as coagulant-aid are presented in **Table 2**. Combination of alginate with coagulant such as PAC, $AlCl_3$, $Al_2(SO_4)_3$, $FeCl_3$, and $CaCl_2$ has been reported to treat various types of water or wastewater such as, turbidity, dyes, textile wastewater, leachate, and microplastic suspension. The coagulation performance, indicated by turbidity or pollutant removal, varies due to several factors. One major factor is the type of coagulant and its dose. For example, high removal efficiency (≥ 98%) was generally observed with $CaCl_2$ or $AlCl_3$ in synthetic or low-complexity dye wastewater, where alginate can form strong ionic bridges due to divalent or trivalent cation cross-linking. The pH of the system also plays a critical role; optimal coagulation typically occurred near neutral pH (6.5 –7.6), where alginate maintains high solubility and functional group availability for floc formation. Another key factor is the wastewater complexity. For instance, landfill leachate showed lower removal efficiencies (54–80%), likely due to the presence of competing organic and colloidal substances, which hinder effective coagulation and flocculation. The dose of alginate also influences performance; too low may be insufficient for bridging, while excess alginate can lead to re-stabilization of particles. Moreover, studies that used humic acid or reactive dyes with low molecular weight organics reported moderate removal efficiencies (66–85%), indicating that the interaction mechanism between alginate and dissolved organic matter may be less effective compared to particulate or dye-laden wastewater. This highlights the importance of optimizing coagulant:coagulant-aid ratios and adjusting the coagulation condition to the specific characteristics of the wastewater.

Further comparison of alginate performance with other polysaccharides that act as coagulant-aid is presented in **Table 3**. Sodium alginate, combined with inorganic coagulants, can achieve turbidity removal up to 99%. This performance is comparable with other natural coagulant-aid such as sesbania seed gum (98.3%) or pectin (99.6%). The required alginate dose is also within the same range as other coagulant-aids. This comparison shows alginate's potential as a natural coagulant-aid, though direct comparative studies are still needed to fully evaluate its relative performance.

4. RECENT STRATEGIES TO IMPROVE ALGINATE'S COAGULATION PERFORMANCE

To improve the coagulation efficiency of alginate, several strategies can be implemented, namely modifying alginate by introducing copolymers into the alginate structure and incorporating magnetic nanoparticles to the coagulation system.

4.1. Alginate modification as coagulant/ flocculant

There are several studies that explored the modification of alginate by introducing cationic groups via grafting, crosslinking, or other methods. Several chemicals that has been used as copolymer such as acrylamide [79], methacryloxyethyltrimethyl ammonium chloride [80], polyacrylamide [81], poly (*N,N*-dimethylacrylamide) [82], 3-chloro-2-hydroxypropyltrimethylammonium chloride [83]. Modification of sodium alginate has been reported to increase its flocculation performance, due to the dangling copolymer structure has a better approachability to the colloid particles that result in a more effective bridging mechanism [79]. Furthermore, the positively charged quaternary ammonium groups on the modified alginate can interact with the colloids via charge neutralization mechanism [80]. Illustration regarding the grafting

Table 2. Optimum condition of alginate as coagulant-aid.

Coagulant	Wastewater Characteristics	Coagulant Dose (mg/L)	Alginate Dose (mg/L)	pH	Results	Ref.
$CaCl_2$ + sodium alginate	Synthetic kaolin wastewater 300 NTU	200	10	7.55	99.3%	[51]
PAC + sodium alginate	Dispersive yellow RGFL 100 mg/L	6	1	6	97.0%	[84]
PAC + sodium alginate	Reactive blue KGL 100 mg/L	8	1	6	97.0%	[84]
PAC + sodium alginate	Humic acid Dissolved organic carbon (DOC) 4.52 mg/L	4	0.3	6	74.0%	[84]
$CaCl_2$ + sodium alginate	Sulphur black dye 200 mg/L	6000	30	n/a	98.2%	[85]
$CaCl_2$ + sodium alginate	Acid black 1 dye 1000 mg/L	6000	40	4.2	96.8%	[86]
$CaCl_2$ + sodium alginate	Reactive magenta dye 100 PtCo	4000	30	4.6	92.7%	[87]
$CaCl_2$ + sodium alginate	Congo red dye 250 mg/L	6000	60	4	96.0%	[88]
$CaCl_2$ + sodium alginate	Crystal violet dye 1,000 mg/L	6000	50	9.4	97.3%	[89]
PAC + sodium alginate	Humic acid Dissolved organic carbon (DOC) 4.52 mg/L	6	0.3	7.7	66.5%	[90]
$AlCl_3$ + sodium alginate	Sidi Said Maachou dam water Turbidity 100 NTU Permanganate value 7.16 mgO_2/L	4	1.6	7.6	98.0% turbidity 36.0% organic substances	[91]
$FeCl_3$ + sodium alginate	Landfill leachate sample Turbidity 154 NTU COD 2,958 mg/L	2500	120	6.5	80.0% turbidity 54.0% COD	[68]
$Al_2(SO_4)_3$ + sodium alginate	Textile wastewater COD 2860 mg/L	65	1	6–8	80.1%	[57]
PAC + sodium alginate	PET microplastic suspension 100 mg	200	100	n/a	73.4%	[92]

of sodium alginate with copolymer is presented in **Figure 4**. The commonly used reaction by using a radical initiator such as persulfate ion ($S_2O_8^{2-}$) with external energy source such as microwave or ultrasonic irradiation that would initiate the reaction (**Figure 4(a)**). Those radicals would attack the hydroxide functional groups of alginate structure, resulting in oxygen radicals that would react with the copolymer. A more detailed discussion regarding the modification techniques on sodium alginate has been discussed in previous review papers [35][37].

4.2. Addition of magnetic nanoparticles to the coagulation system

One of the drawbacks of coagulation-flocculation is the long settling time to separate the flocs from the treated water, that typically 1 to 2 h settling time is needed. The long settling time is proportional to the clarifier size that is needed for flocs sedimentation. This challenge can be overcome by incorporating magnetic nanoparticles such as Fe_3O_4, α-Fe_2O_3, and γ-Fe_2O_3 [17][99]. For this purpose, magnetic coagulant can be first synthesized by dispersing the magnetic nanoparticle into the coagulant solution [100]. Tang et al (2019) reported that during this step, interaction between Fe_3O_4 and PAC coagulant could occur via an oxygen bridge [101]. After the dispersion step, the magnetic coagulant is added to the system, followed by sodium alginate as coagulant-aid. Suhardi et al. (2024) reported the synergistic combination of coagulant, magnetic nanoparticles, and sodium alginate has resulted in significantly lower settling time, 20 min, compared to coagulation that only used PAC (60 min), while increasing the coagulation performance from 48 to 81% of Congo red dye removal [59]. The schematic illustration of magnetic coagulation with the presence of sodium alginate is presented in **Figure 5(a)**. Similar to the coagulation mechanism discussed previously in Section 3.1., the alginate acts as particle bridge, resulting in bigger floc formation (**Figure 5(c)**), compared to magnetic coagulant only (**Figure 5 (b)**). Additionally, it is possible to separate the magnetic nanoparticles for regeneration and reused to improve its sustainability. While these results are promising, the application of magnetic coagulation remains largely limited to laboratory-scale studies,

Table 3. Comparison of alginate performance with other polysaccharide as coagulant-aid.

Coagulant	Wastewater Characteristics	Coagulant Dose (mg/L)	Alginate Dose (mg/L)	pH	Results	Ref.
$CaCl_2$ + sodium alginate	Synthetic kaolin wastewater 300 NTU	200	10	7.55	99.3%	[51]
$AlCl_3$ + sodium alginate	Sidi Said Maachou dam water Turbidity 100 NTU	4	1.6	7.6	98.0%	[91]
$AlCl_3$ + citrus pectin	Synthetic kaolin wastewater 0.4 g/L	133.33	7.59	5.45	99.6%	[93]
$FeCl_3$ + sesbania seed gum	Inlet of Sultan Idris Shah II water treatment plant 285 NTU	10.2	4.52	6.4	98.3%	[94]
$Al_2(SO_4)_3$ + guar gum	Inlet of Fofanny water treatment plant 26.5 NTU	44.97	1.8	5.79	96.2%	[95]
PAC + xanthan gum	Campo river water 69 NTU	5	0.6	7.7	97.4%	[96]
$Al_2(SO_4)_3$ + apricot gum	Synthetic turbid water 100 NTU	6	6	7.0	83.0%	[97]

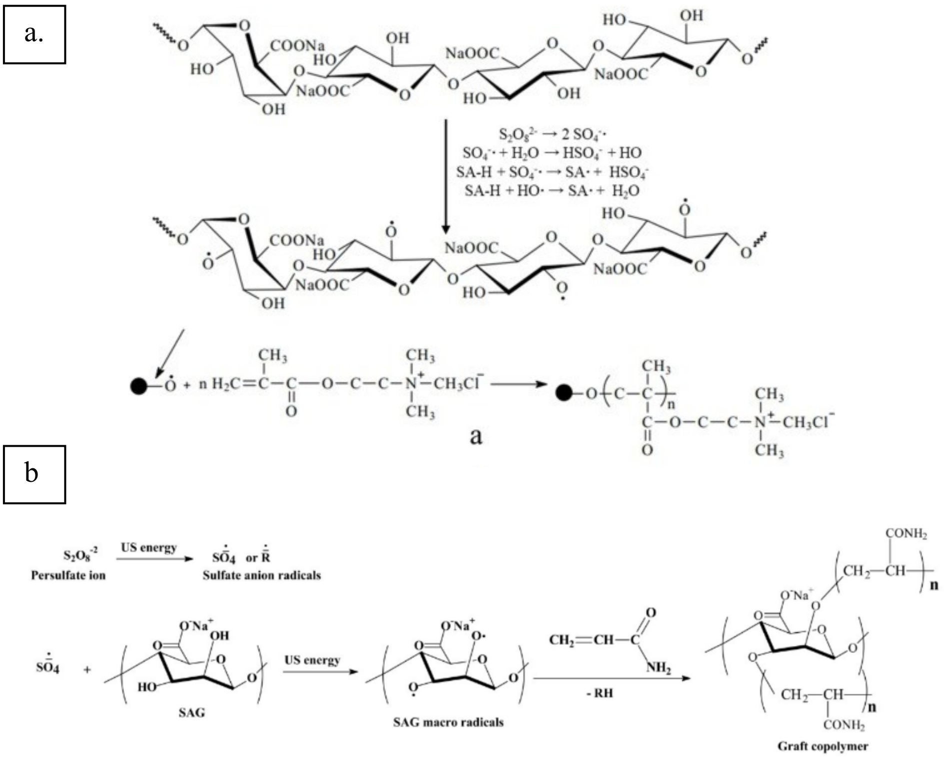

Figure 4. Sodium alginate grafting reaction with (a) methacryloxyethyltrimethyl ammonium chloride [80] and (b) acrylamide [98].

with minimal exploration at the pilot or industrial scale. Furthermore, the integration of alginate in a magnetic coagulation system has been scarcely investigated, underlining the need for further investigation into its specific interactions and functional role within such systems. A more comprehensive overview of magnetic coagulation systems and their potential application has been covered by several recent review papers [17][102]-[104].

5. CHALLENGES AND OUTLOOK

Although alginate has shown a great potential for its application as coagulant-aid, there are some challenges that need to be overcome before its further utilization and commercialization. It has been shown previously that the composition of G and M block in the alginate structure played an important role during coagulation. As previously discussed, alginate can be derived from different sources, such as brown seaweed and several bacteria. Furthermore, its production and purification steps also affect the quality of the alginate produced [105]. These variations can lead into the variability of alginate composition, molecular weight, and its ability to interact with metal cations. Thus, further study regarding application of sodium alginate from various sources along with information of its characteristics as coagulant-aid is needed. This information can be important to establish a standard and criteria of alginate properties for coagulant-aid application.

Another key issue is the availability and the price of alginate. In online marketplace, price for sodium alginate is ranging from US$ 5–15/kg depending on its quality and grade. This price is higher than polyacrylamide, ranging from US$ 1–2/kg. Similar issues of cost have been raised by other researchers, where the cost of natural coagulant or coagulant-aid is still higher than commercial inorganic/ synthetic coagulant [18][106][107]. The high cost can become a hindrance that make industries reluctant to shift from inorganic coagulant to natural coagulant that need further attention from regulators. Several strategies can be employed to reduce the cost of alginate production. These include production of alginate from bacterial sources, utilization of seaweed waste, and process intensification-optimization in alginate production. Bacterial alginate offers some advantages, including controlled yield and alginate properties,

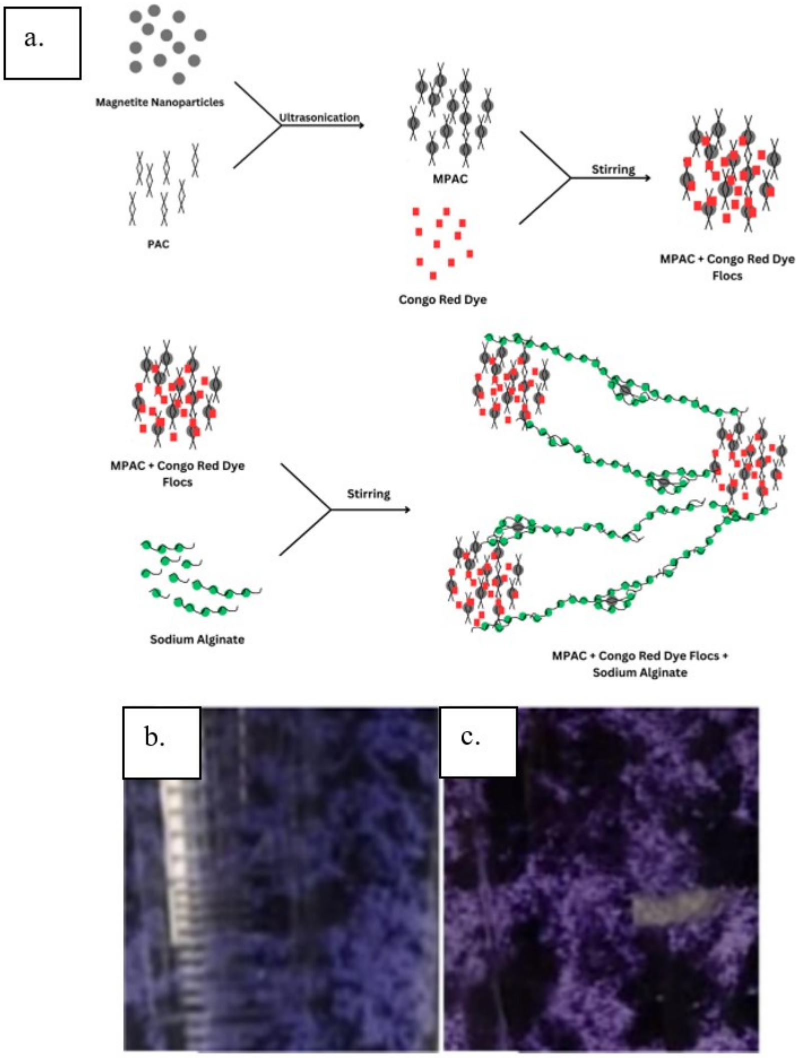

Figure 5. (a) Coagulation mechanism of magnetic coagulant and sodium alginate, (b) visual observation of floc after coagulation with magnetic coagulant, and (c) magnetic coagulant + sodium alginate [59].

reproducible physicochemical properties [105], and the potential use of carbon-rich waste and industrial byproducts as fermentation substrates, which could lower the production cost and enhance sustainability [41]. Additionally, the valorization of underutilized seaweed waste, such as *Laminaria* roots, has demonstrated cost-effective potential for alginate production [108]. Lastly, process intensification and optimization of production process can lead to more efficient alginate production by minimizing the consumption of energy, utility, chemicals, etc. that resulted in a more economically viable and environmentally friendly production system [109]. Furthermore, most of the studies that used alginate as coagulant-aid are limited to laboratory scale, thus its application in pilot and industrial scale needs to be investigated, to validate its performance for real water/wastewater treatment, as well as evaluating its economic feasibility. In general, such pilot and industrial scale study of natural coagulant and coagulant-aid remain scarce [14][17][103], highlighting a valuable opportunity for future studies.

There is a limited study on the characteristics of sludge generated from the use of alginate as coagulant-aid, particularly in terms of its dewatering properties, biodegradability, and the long-term environmental impacts. Furthermore, there is no information regarding its interaction with ecosystem and degradation byproducts, especially for modified alginate products. This poses uncertainties regarding their ecological effects. Moreover, there is also a promising opportunity to valorise the alginate-based sludge such as feedstock for biogas production [110], organic fertilizer in agriculture [111], and soil preservation [112]; depending on the content of the sludge. These applications could enhance its sustainability and contribute to the principles of circular economy. Finally, a comprehensive study regarding its environmental, economic, and social impact via life cycle assessment (LCA) is necessary. Although there are some studies reporting the LCA for alginate production [113][114], as well as other applications using alginate [115][116], there are no such studies available regarding the use of alginate as coagulant-aid. On the other hand, there are some studies regarding LCA of natural coagulant and coagulant-aid in water/wastewater treatment. These studies have affirmed that the use of natural resources gave low environmental impact due to low chemical consumption and more simple coagulant production [117][118]. This absence of LCA in the context of alginate as a coagulant-aid highlights a clear niche for future research. Conducting LCA study can give a clear cradle-to-grave cycle of alginate application as coagulant-aid, from its extraction and production to sludge disposal with potential reuse, ensuring that the adoption of alginate as coagulant-aid in water/ wastewater treatment aligns with long-term sustainability goals.

6. CONCLUSION

In this review, we have explored the potential of alginate as a coagulant-aid in water and wastewater treatment. Alginate can be extracted from various sources, such as brown seaweed and certain bacteria. However, optimizing the production process to yield alginate with a high G content is crucial for its effective use as a coagulant-aid. Sodium alginate, in particular, has been directly applied in treatment processes, and its performance has been demonstrated across a range of applications. Several efforts have been employed to improve the alginate's efficiency, including incorporation of copolymer and the use of magnetic nanoparticles in coagulation. While alginate shows significant promise as a coagulant aid, there are some challenges for its commercialization, such as its availability and price, the issues regarding sludge characteristics, long-term use, and sustainability, that need to be addressed in future studies.

AUTHOR INFORMATION

Corresponding Author

Hans Kristianto — Department of Chemical Engineering, Parahyangan Catholic University, Bandung-40141 (Indonesia);
orcid.org/0000-0003-4747-4361
Email: hans.kristianto@unpar.ac.id

Authors

Susiana Prasetyo — Department of Chemical Engineering, Parahyangan Catholic University, Bandung-40141 (Indonesia);
orcid.org/0000-0001-5839-0054
Asaf Kleopas Sugih — Department of Chemical Engineering, Parahyangan Catholic University, Bandung-40141 (Indonesia);
orcid.org/0000-0003-0478-540X

Author Contributions

Conceptualization, investigation, writing – original draft: H. K. Writing – review & editing: S. P. and A. K. S.

Conflicts of Interest

The authors declare no conflict of interest.

REFERENCES

[1] C. P. Sagita, L. Nulandaya, and Y. S. Kurniawan. (2021). "Efficient and Low-Cost Removal of Methylene Blue using Activated Natural Kaolinite Material". *Journal of Multidisciplinary Applied Natural Science.* **1** (2): 69-77. 10.47352/jmans.v1i2.80.

[2] H. Kristianto, N. Daulay, and A. A. Arie. (2019). "Adsorption of Ni(II) Ion onto Calcined Eggshells: A Study of Equilibrium Adsorption Isotherm". *Indonesian Journal of Chemistry.* **19** (1): 143 - 150. 10.22146/ijc.29200.

[3] S. P. Bera and C. K. Manoj Godhaniya. (2022). "Emerging and advanced membrane technology for wastewater treatment: A review". *Journal of Basic Microbiology.* **62** (3-4): 245-259. 10.1002/jobm.202100259.

[4] T. Hudaya, H. Kristianto, and C. Meliana. (2018). "The Simultaneous Removal of Cyanide and Cadmium Ions from

Electroplating Wastewater using UV/TiO2 Photocatalysis". *International Journal of Technology*. **9** (5): 964-971. 10.14716/ijtech.v9i5.1797.

[5] Kusumlata, B. Ambade, A. Kumar, and S. Gautam. (2024). "Sustainable Solutions: Reviewing the Future of Textile Dye Contaminant Removal with Emerging Biological Treatments". *Limnological Review*. **24** (2): 126-149. 10.3390/limnolrev24020007.

[6] A. K. Verma, R. R. Dash, and P. Bhunia. (2012). "A review on chemical coagulation/ flocculation technologies for removal of colour from textile wastewaters". *Journal of Environmental Management*. **93** : 154-168. 10.1016/j.jenvman.2011.09.012.

[7] H. Kristianto. (2017). "The Potency of Indonesia Native Plants as Natural Coagulant: a Mini Review". *Water Conservation Science and Engineering*. **2** : 51–60. 10.1007/s41101-017-0024-4.

[8] V. Rondeau, D. Commenges, H. Jacqmin-Gadda, and J.-F. Dartigues. (2000). "Relation between aluminum concentrations in drinking water and Alzheimer's disease: an 8-year follow-up study". *American Journal of Epidemiology*. **152** (1): 59-66. 10.1093/aje/152.1.59.

[9] A. A. Nikitina, A. A. Ermoshin, E. A. Zhuravleva, A. A. Kovalev, D. A. Kovalev, V. Panchenko, and Y. V. Litti. (2021). "Application of Polyacrylamide Flocculant for Stabilization of Anaerobic Digestion under Conditions of Excessive Accumulation of Volatile Fatty Acids". *Applied Sciences*. **11** (1): 100. 10.3390/app11010100.

[10] D. P. Weston, R. D. Lentz, M. D. Cahn, R. S. Ogle, A. K. Rothert, and M. J. Lydy. (2009). "Toxicity of Anionic Polyacrylamide Formulations when Used for Erosion Control in Agriculture". *Journal of Environmental Quality*. **38** : 238–247. 10.2134/jeq2008.0109.

[11] K. L. Duggan, M. Morris, S. K. Bhatia, M. M. Khachan, and K. E. Lewis. (2019). "Effects of Cationic Polyacrylamide and Cationic Starch on Aquatic Life". *Journal of Hazardous, Toxic, and Radioactive Waste*. **23** (4): 04019022. 10.1061/(ASCE)HZ.2153-5515.0000467.

[12] Y. C. Ho, I. Norli, A. F. M. Alkarkhi, and N. Morad. (2010). "Characterization of biopolymeric flocculant (pectin) and organic synthetic flocculant (PAM): A comparative study on treatment and optimization in kaolin suspension". *Bioresource Technology*. **101** : 1166–1174. 10.1016/j.biortech.2009.09.064.

[13] C. Y. Teh, P. M. Budiman, K. P. Y. Shak, and T. Y. Wu. (2016). "Recent Advancement of Coagulation–Flocculation and Its Application in Wastewater Treatment". *Industrial and Engineering Chemistry Research*. **55** (16): 4363-4389. 10.1021/acs.iecr.5b04703.

[14] S. B. Kurniawan, S. R. S. Abdullah, M. F. Imron, N. S. M. Said, N. I. Ismail, H. A. Hasan, A. R. Othman, and I. F. Purwanti. (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): 9312. 10.3390/ijerph17249312.

[15] C.-Y. Yin. (2010). "Emerging usage of plant-based coagulants for water and wastewater treatment". *Process Biochemistry*. **45** : 1437-1444. 10.1016/j.procbio.2010.05.030.

[16] S. Y. Choy, K. M. N. Prasad, T. Y. Wu, and R. N. Ramanan. (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. 10.1007/s13762-013-0446-2.

[17] H. Kristianto. (2021). "Recent advances on magnetic natural coagulant: a mini review". *Environmental Technology Reviews*. **10** (1): 254-269. 10.1080/21622515.2021.1986576.

[18] H. Kristianto, N. Manurung, I. K. Wardhani, S. Prasetyo, A. K. Sugih, and A. A. Arbita. (2022). "A kinetic, isotherm adsorption, and thermodynamic study of Congo red coagulation using Leucaena crude extract as natural coagulant". *Water Practice and Technology*. **17** (6): 1332-1346. 10.2166/wpt.2022.058.

[19] J. Kristanda, K. Sandrosa, H. Kristianto, S. Prasetyo, and A. K. Sugih. (2021). "Optimization study of Leucaena leucocephala seeds extract as natural coagulant on decolorization of aqueous Congo red solutions". *Arabian Journal for Science and Engineering.* **46** (7): 6275-6286. 10.1007/s13369-020-05008-1.

[20] M. P. Wagh, Y. Aher, and A. Mandalik. (2022). "Potential of Moringa Oleifera Seed as a Natural Adsorbent for Wastewater Treatment". *Trends in Sciences.* **19** (2): 2019. 10.48048/tis.2022.2019.

[21] Christian, M. J. B. Putra, H. Kristianto, S. Prasetyo, A. K. Sugih, and A. A. Arbita. (2024). "Removal of Congo red and tartrazine binary mixture using Leucaena leucocephala seed's extract as natural coagulant". *IOP Conference Series: Earth and Environmental Science.* **1388** : 012001. 10.1088/1755-1315/1388/1/012001.

[22] A. Ibrahim, A. Z. Yaser, and J. Lamaming. (2021). "Synthesising tannin-based coagulants for water and wastewater application: A review". *Journal of Environmental Chemical Engineering.* **9** (1): 105007. 10.1016/j.jece.2020.105007.

[23] T. Leiviskä and S. C. R. Santos. (2023). "Purifying water with plant-based sustainable solutions: Tannin coagulants and sorbents". *Groundwater for Sustainable Development.* **23** : 101004. 10.1016/j.gsd.2023.101004.

[24] S. M. Asharuddin, N. Othman, W. A. H. Altowayti, N. A. Bakar, and A. Hassan. (2021). "Recent advancement in starch modification and its application as water treatment agent". *Environmental Technology & Innovation.* **23** : 101637. 10.1016/j.eti.2021.101637.

[25] M. M. Sudirgo, R. A. Surya, H. Kristianto, S. Prasetyo, and A. K. Sugih. (2023). "Application of xanthan gum as coagulant-aid for decolorization of synthetic Congo red wastewater". *Heliyon.* **9** (4): E15011. 10.1016/j.heliyon.2023.e15011.

[26] F. Shao, J. Xu, J. Zhang, L. Wei, C. Zhao, X. Cheng, C. Lu, and Y. Fu. (2021). "Study on the influencing factors of natural pectin's flocculation: Their sources, modification, and optimization". *Water Environment Research.* **93** (10): 2261-2273. 10.1002/wer.1598.

[27] F. M. K. Haryanto, A. V. M. Rumondor, H. Kristianto, S. Prasetyo, and A. K. Sugih. (2024). "The Utilization of Pectin as Natural Coagulant-Aid in Congo Red Dye Removal". *Journal of Multidisciplinary Applied Natural Science.* **4** (1): 39-48. 10.47352/jmans.2774-3047.179.

[28] S. Prasetyo, C. A. Santos, A. K. Sugih, and H. Kristianto. (2025). "Utilization of chitosan as a natural coagulant for polyethylene microplastic removal". *Sustainable Chemistry for the Environment.* **9** : 100225. 10.1016/j.scenv.2025.100225.

[29] R. G. Puscaselu, A. Lobiuc, M. Dimian, and M. Covasa. (2020). "Alginate: From Food Industry to Biomedical Applications and Management of Metabolic Disorders". *Polymers.* **12** (10): 2417. 10.3390/polym12102417.

[30] B. Wang, Y. Wan, Y. Zheng, X. Lee, T. Liu, Z. Yu, J. Huang, Y. S. Ok, J. Chen, and B. Gao. (2019). "Alginate-based composites for environmental applications: a critical review". *Critical Reviews in Environmental Science and Technology.* **49** (4): 318-356. 10.1080/10643389.2018.1547621.

[31] A. Benettayeb, M. H. Brahim, B. Lal, S. Al-Farraj, M. Belkacem, M. J. Masamvu, B. Haddou, A. A. Alkahtane, C.-h. Chia, M. Sillanpaa, S. Ghosh, and A. Hosseini-Bandegharaei. (2024). "Insights into logical method selection for modification of chitosan and alginate towards the adsorption of heavy metal ions: a review". *Environmental Technology Reviews.* **13** (1): 398-420 10.1080/21622515.2024.2354519.

[32] S. Radoor, J. Karayil, A. Jayakumar, D. R. Kandel, J. T. Kim, S. Siengchin, and J. Lee. (2024). "Recent advances in cellulose- and alginate-based hydrogels for water and wastewater treatment: A review". *Carbohydrate Polymers.* **323** : 121339. 10.1016/j.carbpol.2023.121339.

[33] D. Yadav and J. Dutta. (2024). "A systematic review on recent development of chitosan/ alginate-based polyelectrolyte complexes for wastewater treatmentAlginate-based

composites for environmental applications: A critical review". *International Journal of Environmental Science and Technology.* **21** : 3381-3406. 10.1007/s13762-023-05244-6.

[34] F. Rafiee. (2023). In: " Alginate - Applications and Future Perspectives, I. A. Severo, A. B. Mariano, and J. V. C. Vargas Eds., " IntechOpen. 10.5772/intechopen.110148.

[35] H. Guo, Q. Qin, J.-S. Chang, and D.-J. Lee. (2023). "Modified alginate materials for wastewater treatment: Application prospects". *Bioresource Technology.* **387** : 129639. 10.1016/j.biortech.2023.129639.

[36] E. A. López-Maldonado, Y. Abdellaoui, M. H. A. Elella, H. M. Abdallah, M. Pandey, E. T. Anthony, L. Ghimici, S. Álvarez-Torrellas, V. Pinos-Vélez, and N. A. Oladoja. (2024). "Innovative biopolyelectrolytes-based technologies for wastewater treatment". *International Journal of Biological Macromolecules.* **273** : 132895. 10.1016/j.ijbiomac.2024.132895.

[37] B. Kumar, N. Singh, and P. Kumar. (2024). "A review on sources, modification techniques, properties and potential applications of alginate-based modified polymers". *European Polymer Journal.* **213** : 113078. 10.1016/j.eurpolymj.2024.113078.

[38] P. Saranya, S. T. Ramesh, and R. Gandhimathi. (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. 10.1080/19443994.2013.812993.

[39] W. L. Ang and A. W. Mohammad. (2020). "State of the art and sustainability of natural coagulants in water and wastewater treatment". *Journal of Cleaner Production.* **262** : 121267. 10.1016/j.jclepro.2020.121267.

[40] M. M. Rahman, M. A. Shahid, M. T. Hossain, M. S. Sheikh, M. S. Rahman, N. Uddin, A. Rahim, R. A. Khan, and I. Hossain. (2024). "Sources, extractions, and applications of alginate: a review". *Discover Applied Sciences.* **6** : 443. 10.1007/s42452-024-06151-2.

[41] J. Wang, S. Liu, J. Huang, K. Ren, Y. Zhu, and S. Yang. (2023). "Alginate: Microbial production, functionalization, and biomedical applications". *International Journal of Biological Macromolecules.* **242** : 125048. 10.1016/j.ijbiomac.2023.125048.

[42] K. Y. Lee and D. J. Mooney. (2012). "Alginate: Properties and biomedical applications". *Progress in Polymer Science.* **37** (1): 106-126. 10.1016/j.progpolymsci.2011.06.003.

[43] O. Smidsrød. (1970). "Solution properties of alginate". *Carbohydrate Research.* **13** (3): 359-372. 10.1016/S0008-6215(00)80593-5.

[44] E. ANS, M. Younes, P. Aggett, F. Aguilar, R. Crebelli, M. Filipič, M. J. Frutos, P. Galtier, D. Gott, U. Gundert-Remy, G. G. Kuhnle, C. Lambré, J.-C. Leblanc, I. T. Lillegaard, P. Moldeus, A. Mortensen, A. Oskarsson, I. Stankovic, I. Waalkens-Berendsen, R. A. Woutersen, L. B. Matthew Wright, O. Lindtner, P. Mosesso, A. Christodoulidou, Z. Horváth, F. Lodi, and B. Dusemund. (2017). "Re-evaluation of alginic acid and its sodium, potassium, ammonium and calcium salts (E 400–E 404) as food additives". *EFSA Journal.* **15** (11): e05049. 10.2903/j.efsa.2017.5049.

[45] M. S. Hasnain, E. Jameel, B. Mohanta, A. K. Dhara, S. Alkahtani, and A. K. Nayak. (2020). In: "Alginates in Drug Delivery". Elsevier Inc. 10.1016/B978-0-12-817640-5.00001-7.

[46] M. J. Costa, A. M. Marques, L. M. Pastrana, J. A. Teixeira, S. M. Sillankorva, and M. A. Cerqueira. (2018). "Physicochemical properties of alginate-based films: Effect of ionic crosslinking and mannuronic and guluronic acid ratio". *Food Hydrocolloids.* **81** : 442-448. 10.1016/j.foodhyd.2018.03.014.

[47] P. Agulhon, M. Robitzer, J.-P. Habas, and F. Quignard. (2014). "Influence of both cation and alginate nature on the rheological behavior of transition metal alginate gels". *Carbohydrate Polymers.* **112** : 525-531. 10.1016/j.carbpol.2014.05.097.

[48] S. B. Kurniawan, M. F. Imron, C. E. N. C. E. Chik, A. A. Owodunni, A. Ahmada, M. M.

Alnawajha, N. F. M. Rahim, N. S. M. Said, S. R. S. Abdullah, N. A. Kasan, S. Ismail, A. R. Othman, and H. A. Hasan. (2022). "What compound inside biocoagulants/ bioflocculants is contributing the most to the coagulation and flocculation processes?". *Science of the Total Environment.* **806** : 150902. 10.1016/j.scitotenv.2021.150902.

[49] M. Yao, J. Nan, Q. Li, D. Zhan, T. Chen, Z. Wang, and H. Li. (2015). "Effect of under-dosing coagulant on coagulation–ultrafiltration process for treatment of humic-rich water with divalent calcium ion". *Journal of Membrane Science.* **495** : 37-47. 10.1016/j.memsci.2015.08.001.

[50] M. T. Khan, M. Ahmad, M. F. Hossain, A. Nawab, I. Ahmad, K. Ahmad, and S. Panyametheekul. (2023). "Microplastic removal by coagulation: a review of optimizing the reaction conditions and mechanisms". *Water Emerging Contaminants and Nanoplastics.* **2** : 22. 10.20517/wecn.2023.39

[51] P. Saranya, S. T. Ramesh, and R. Gandhimathi. (2022). "Coagulation performance evaluation of alginate as a natural coagulant for the treatment of turbid water ". *Water Practice and Technology.* **17** (1): 395-404. 10.2166/wpt.2021.123.

[52] H. A. Devrimci, A. M. Yuksel, and F. D. Sanin. (2012). "Algal alginate: A potential coagulant for drinking water treatment". *Desalination.* **299** : 16–21. 10.1016/j.desal.2012.05.004.

[53] D. Ghernaout and B. Ghernaout. (2012). "Sweep flocculation as a second form of charge neutralisation—a review". *Desalination and Water Treatment.* **44** (1-3): 15-28. 10.1080/19443994.2012.691699.

[54] Ç. K. Moral, H. Ertesvåg, and F. D. Sanin. (2016). "Guluronic acid content as a factor affecting turbidity removal potential of alginate". *Environmental Science and Pollution Research.* **23** : 22568–22576. 10.1007/s11356-016-7475-6.

[55] H. Kristianto, A. Jennifer, A. K. Sugih, and S. Prasetyo. (2020). "Potensi Polisakarida dari Limbah Buah-buahan sebagai Koagulan Alami dalam Pengolahan Air dan Limbah Cair: Review". *Jurnal Rekayasa Proses.* **14** (2): 108-127. 10.22146/jrekpros.57798.

[56] Y. X. Zhao, Y. Wang, B. Y. Gao, H. K. Shon, J. H. Kim, and Q. Y. Yue. (2012). "Coagulation performance evaluation of sodium alginate used as coagulant aid with aluminum sulfate, iron chloride and titanium tetrachloride". *Desalination.* **299** : 79–88. 10.1016/j.desal.2012.05.026.

[57] C. Wu, Y. Wang, B. Gao, Y. Zhao, and Q. Yue. (2012). "Coagulation performance and floc characteristics of aluminum sulfate using sodium alginate as coagulant aid for synthetic dying wastewater treatment". *Separation and Purification Technology.* **95** : 180-187. 10.1016/j.seppur.2012.05.009.

[58] Y. X. Zhao, B. Y. Gao, Y. Wang, H. K. Shon, X. W. Bo, and Q. Y. Yue. (2012). "Coagulation performance and floc characteristics with polyaluminum chloride using sodium alginate as coagulant aid: A preliminary assessment". *Chemical Engineering Journal.* **183** : 387-394. 10.1016/j.cej.2012.01.036.

[59] E. D. Suhardi, F. V. Hermawan, H. Kristianto, S. Prasetyo, and A. K. Sugih. (2024). "Enhancing water–wastewater treatment efficiency: synergistic approach using polyaluminum chloride, sodium alginate, and magnetite for Congo red removal". *Chemical Papers.* **78** : 3971-3981. 10.1007/s11696-024-03367-9.

[60] A.-A. E. Foulani, O. Ounas, M. Tahiri, and M. Chafi. (2023). "A Comparative Study of the Performance of Polyaluminum Chloride-Sodium Alginate and Polyaluminum Chloride-Chitosan Composite Coagulants in Dam Water Treatment". *Journal of Polymers and the Environment.* **31** : 4909-4918. 10.1007/s10924-023-02930-x.

[61] M. Assou, L. E. Fels, A. E. Asli, H. Fakidi, S. Souabi, and M. Hafidi. (2016). "Landfill leachate treatment by a coagulation–flocculation process: effect of the introduction order of the reagents". *Desalination and Water Treatment.* **57** (46): 21817-21826. 10.1080/19443994.2015.1127779.

[62] J. Naceradska, L. Pivokonska, and M. Pivokonsky. (2019). "On the importance of pH value in coagulation". *Journal of Water Supply: Research and Technology - AQUA.* **68** (3): 222-230. 10.2166/aqua.2019.155.

[63] K. Pate and P. Safier. (2016). "12 - Chemical metrology methods for CMP quality". *Advances in Chemical Mechanical Planarization (CMP).* 299-325. 10.1016/B978-0-08-100165-3.00012-7.

[64] L. Ramirez, S. R. Gentile, S. Zimmermann, and S. Stoll. (2016). "Comparative Study of the Effect of Aluminum Chloride, Sodium Alginate and Chitosan on the Coagulation of Polystyrene Micro-Plastic Particles". *Journal of Colloid Science and Biotechnology.* **5** (2): 190-198. 10.1166/jcsb.2016.1149.

[65] J.-Q. Jiang. (2015). "The role of coagulation in water treatment". *Current Opinion in Chemical Engineering.* **8** : 36-44. 10.1016/j.coche.2015.01.008.

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

[67] I. M. T. Usman, Y.-C. Ho, L. Baloo, M.-K. Lam, P.-L. Show, and W. Sujarwo. (2023). "Comprehensive Review of Modification, Optimisation, and Characterisation Methods Applied to Plant-Based Natural Coagulants (PBNCs) for Water and Wastewater Treatment". *Sustainability.* **15** (5): 4484. 10.3390/su15054484.

[68] M. Kastali, L. Mouhir, M. Assou, A. Anouzla, and Y. Abrouki. (2020). "Diagnosis of leachate from a closed landfill, impact on the soil, and treatment by coagulation flocculation with alginate and ferric chloride". *Desalination and Water Treatment.* **206** 307-314. 10.5004/dwt.2020.26303.

[69] H. Kristianto, A. Jennifer, S. Prasetyo, and A. K. Sugih. (2022). "A preliminary study on the utilization of gelatinized durian starch as natural coagulant aid in synthetic Congo red wastewater treatment". *AIP Conference Proceedings.* **2645** : 030001. 10.1063/5.0113622.

[70] N. A. Awang and H. A. Aziz. (2012). "Hibiscus rosa-sinensis leaf extract as coagulant aid in leachate treatment ". *Applied Water Science.* **2** 293–298. 10.1007/s13201-012-0049-y.

[71] S. Bouissil, Z. E. Alaoui-Talibi, G. Pierre, P. Michaud, C. E. Modafar, and C. Delattre. (2020). "Use of Alginate Extracted from Moroccan Brown Algae to Stimulate Natural Defense in Date Palm Roots". *Molecules.* **25** (3): 720. 10.3390/molecules25030720.

[72] A. Mohammed, R. Bissoon, E. Bajnath, K. Mohammed, T. Lee, M. Bissram, N. John, N. K. Jalsa, K.-Y. Lee, and K. Ward. (2018). "Multistage extraction and purification of waste Sargassum natans to produce sodium alginate: An optimization approach". *Carbohydrate Polymers.* **198** : 109-118. 10.1016/j.carbpol.2018.06.067.

[73] J. E. Ogbezode, U. S. Ezealigo, A. Bello, V. C. Anye, and A. P. Onwualu. (2023). "A narrative review of the synthesis, characterization, and applications of iron oxide nanoparticles". *Discover Nano.* **18** : 125.

[74] M. Fertah, A. Belfkira, E. Dahmane, M. Taourirte, and F. Brouillette. (2017). "Extraction and characterization of sodium alginate from Moroccan Laminaria digitata brown seaweed". *Arabian Journal of Chemistry.* **10** : S3707–S3714. j.arabjc.2014.05.003.

[75] M. R. Torres, A. P. A. Sousa, E. A. T. S. Filho, D. F. Melo, J. P. A. Feitosa, R. C. M. d. Paula, and M. G. S. Lima. (2007). "Extraction and physicochemical characterization of Sargassum vulgare alginate from Brazil". *Carbohydrate Research.* **342** (14): 2067-2074. 10.1016/j.carres.2007.05.022.

[76] A. Díaz-Barrera, F. Sanchez-Rosales, C. Padilla-Córdova, R. Andler, and C. Peña. (2021). "Molecular weight and guluronic/mannuronic ratio of alginate produced by Azotobacter vinelandii at two bioreactor scales under diazotrophic conditions".

Bioprocess and Biosystems Engineering. **44** : 1275-1287. 10.1007/s00449-021-02532-8.

[77] N. Schürks, J. Wingender, H.-C. Flemming, and C. Mayer. (2002). "Monomer composition and sequence of alginates from Pseudomonas aeruginosa". *International Journal of Biological Macromolecules*. **30** (2): 105-111. 10.1016/S0141-8130(02)00002-8.

[78] G. Skjak-Bræk, H. Grasdalen, and B. Larsen. (1986). "Monomer sequence and acetylation pattern in some bacterial alginates". *Carbohydrate Research*. **154** (1): 239-250. 10.1016/S0008-6215(00)90036-3.

[79] A. Sand, A. Vyas, and A. K. Gupta. (2016). "Graft copolymer based on (sodium alginate-g-acrylamide): Characterization and study of Water swelling capacity, metal ion sorption, flocculation and resistance to biodegradability". *International Journal of Biological Macromolecules*. **90** : 37-43. 10.1016/j.ijbiomac.2015.11.085.

[80] C. Liu, B. Gao, S. Wang, K. Guo, X. Shen, Q. Yue, and X. Xu. (2020). "Synthesis, characterization and flocculation performance of a novel sodium alginate-based flocculant". *Carbohydrate Polymers*. **248** : 116790. 10.1016/j.carbpol.2020.116790.

[81] P. Rani, P. Pal, J. P. Panday, S. Mishra, and G. Sen. (2019). "Alginic Acid Derivatives: Synthesis, Characterization and Application in Wastewater Treatment". *Journal of Polymers and the Environment*. **27** : 2769-2783. 10.1007/s10924-019-01553-5.

[82] T. Tripathy, H. Kolya, and S. Jana. (2018). "Selective Lead(II) Adsorption and Flocculation Characteristics of the Grafted Sodium Alginate: A Comparative Study". *Journal of Polymers and the Environment*. **26** : 926-937. 10.1007/s10924-017-1004-7.

[83] Z. Tian, L. Zhang, X. Sang, G. Shi, and C. Ni. (2020). "Preparation and flocculation performance study of a novel amphoteric alginate flocculant". *Journal of Physics and Chemistry of Solids*. **141** : 109408. 10.1016/j.jpcs.2020.109408.

[84] Y. Wang, F. Zhang, Y. Chu, B. Gao, and Q. Yue. (2013). "The dye or humic acid water treatment and membrane fouling by polyaluminum chloride composited with sodium alginate in coagulation–ultrafiltration process". *Water Science and Technology*. **67** (10): 2202-2209. 10.2166/wst.2013.106.

[85] G. Vijayaraghavan and S. Shanthakumar. (2015). "Removal of Sulphur Black Dye from its Aqueous Solution Using Alginate from Sargassum sp. (Brown Algae) as a Coagulant". *Environmental Progress and Sustainable Energy*. **34** (5): 1427–1434. 10.1002/ep.12144.

[86] G. Vijayaraghavan and S. Shanthakumar. (2018). "Effective Removal of Acid Black 1 Dye in Textile Effluent Using Alginate from Brown Algae as a Coagulant". *Iranian Journal of Chemistry and Chemical Engineering*. **37** (4): 145-151. 10.30492/ijcce.2018.35074.

[87] G. Vijayaraghavan and S. Shanthakumar. (2018). "Effective removal of Reactive Magenta dye in textile effuent by coagulation using algal alginate". *Desalination and Water Treatment*. **121** : 22-27. 10.5004/dwt.2018.22190.

[88] G. Vijayaraghavan and S. Shanthakumar. (2016). "Performance study on algal alginate as natural coagulant for the removal of Congo red dye". *Desalination and Water Treatment*. **57** : 6384–6392. 10.1080/19443994.2015.1008578.

[89] G. Vijayaraghavan and S. Shanthakumar. (2020). "Removal of Crystal violet dye in textile effluent by coagulation using algal alginate from brown algae Sargassum sp.". *Desalination and Water Treatment*. **196** : 402-408. 10.5004/dwt.2020.25569.

[90] Y. Wang, X. Li, C. Wu, Y. Zhao, B.-Y. Gao, and Q. Yue. (2014). "The role of sodium alginate in improving floc size and strength and the subsequent effects on ultrafiltration membrane fouling". *Environmental Technology*. **35** (1): 10-17. 10.1080/09593330.2013.800589.

[91] A.-A. E. Foulani, O. Ounas, A. Laabi, B. Lekhlif, and J. Jamal-Eddine. (2020). "Removal of dissolved and colloidal matter from surface waters by composite flocculant aluminum salt-sodium alginate".

Desalination and Water Treatment. **207** : 108 -114. 10.5004/dwt.2020.26407.

[92] Y. Zhang, G. Zhou, J. Yue, X. Xing, Z. Yang, X. Wang, Q. Wang, and J. Zhang. (2021). "Enhanced removal of polyethylene terephthalate microplastics through polyaluminum chloride coagulation with three typical coagulant aids". *Science of the Total Environment.* **800** : 149589. 10.1016/j.scitotenv.2021.149589.

[93] Y. C. Ho, I. Norli, A. F. M. Alkarkhi, and N. Morad. (2009). "Analysis and optimization of flocculation activity and turbidity reduction in kaolin suspension using pectin as a biopolymer flocculant". *Water Science and Technology.* **60** (3): 771-781. 10.2166/wst.2009.303.

[94] S.-C. Chua, F.-K. Chong, M. A. Malek, M. R. U. Mustafa, N. Ismail, W. Sujarwo, J.-W. Lim, and Y.-C. Ho. (2020). "Optimized Use of Ferric Chloride and Sesbania Seed Gum (SSG) as Sustainable Coagulant Aid for Turbidity Reduction in Drinking Water Treatment". *Sustainability.* **12** (6): 2273. 10.3390/su12062273.

[95] B. S. Gupta and J. E. Ako. (2005). "Application of guar gum as a flocculant aid in food processing and potable water treatment ". *European Food Research and Technology*. **221** : 746–751. 10.1007/s00217-005-0056-4.

[96] L. G. Vernasqui, P. Valderrama, and F. V. Silva-Medeiros. (2016). "Xanthan gum as a novel flocculant aid employed in drinking water treatment". *Brazilian Journal of Food Technology.* **7** (3): 52-65. 10.3895/rebrapa.v7n3.3772.

[97] A. H. Ali, Y. S. Tlaiaa, and Z. A. R. Nasir. (2019). "Sustainable Used of Natural Coagulants Aid for Enhancing the Performance of Alum to Treat Turbid Water". *IOP Conference Series: Materials Science and Engineering.* **518** : 022014. 10.1088/1757-899X/518/2/022014.

[98] J. M. C. d. Feira, J. M. Klein, and M. M. D. C. Forte. (2018). "Ultrasound-assisted synthesis of polyacrylamide-grafted sodium alginate and its application in dye removal". *Polimeros.* **28** (2): 139-146. 10.1590/0104-1428.11316

[99] M. H. M. Noor, S. Wong, N. Ngadi, I. M. Inuwa, and L. A. Opotu. (2021). "Assessing the effectiveness of magnetic nanoparticles coagulation/flocculation in water treatment: a systematic literature review". *International Journal of Environmental Science and Technology.* 10.1007/s13762-021-03369-0.

[100] A. K. Sugih, M. A. Deiza, S. F. Nurmawan, S. Prasetyo, D. Tan, and H. Kristianto. (2025). "Combination of FeCl3 and Fe3O4 as a Magnetic Coagulant for Congo Red Removal". *Indonesian Journal of Urban and Environmental Technology.* **8** (1): 99-115. 10.25105/urbanenvirotech.v8i1.22575.

[101] J. Tang, J. Wang, H. Jia, H. Wen, J. Li, W. Liu, and J. Li. (2019). "The investigation on Fe3O4 magnetic flocculation for high efficiency treatment of oily micro-polluted water". *Journal of Environmental Management.* **244** : 399-407. 10.1016/j.jenvman.2019.05.068.

[102] M. H. M. Noor, S. Wong, N. Ngadi, I. M. Inuwa, and L. A. Opotu. (2022). "Assessing the effectiveness of magnetic nanoparticles coagulation/ flocculation in water treatment: a systematic literature review". *International Journal of Environmental Science and Technology.* **19** : 6935-6956. 10.1007/s13762-021-03369-0.

[103] A. K. Badawi, R. S. Salama, and M. M. M. Mostafa. (2023). "Natural-based coagulants/ flocculants as sustainable market-valued products for industrial wastewater treatment: a review of recent developments". *RSC Advances.* **13** : 19335. 10.1039/D3RA01999C.

[104] E. A. López-Maldonado, N. A. Khan, S. Singh, P. C. Ramamurthy, B. Kabak, J. R. V. Baudrit, M. Q. A. Silvia, Álvarez-Torrellas, R. Varshney, E. Serra-Pérez, J. García, D. A. Gkika, G. Z. Kyzas, A. Kadier, R. Singh, S. Periyasamy, D. G. Gizaw, N. Hossain, and S. Zahmatkesh. (2024). "Magnetic polymeric composites: discover their potential for separating and degrading micro/nano plastics". *Desalination and Water Treatment.*

In press : 100198. 10.1016/j.dwt.2024.100198.

[105] V. Urtuvia, N. Maturana, F. Acevedo, C. Peña, and A. Díaz-Barrera. (2017). "Bacterial alginate production: an overview of its biosynthesis and potential industrial production". *World Journal of Microbiology and Biotechnology.* **33** : 198. 10.1007/s11274-017-2363-x.

[106] C. S. Lee. (2017). "Extraction of bio-flocculant from okra using hydrothermal and microwave extraction methods combined with a techno-economic assessment". PhD thesis, University of Nottingham.

[107] W. C. Zheng, N. Ismail, C. O. Boboi, and C. B. Lin. (2021). "Life Cycle Analysis for Hibiscus Sabdariffa Powder Manufactured by Freeze Drying for Wastewater Application". *MATEC Web of Conferences.* **335** : 01002. 10.1051/matecconf/202133501002.

[108] X.-H. Sun, X.-L. Chen, X.-F. Wang, X.-R. Zhang, X.-M. Sun, M.-L. Sun, X.-Y. Zhang, Y.-Z. Zhang, Y.-Q. Zhang, and F. Xu. (2023). "Cost-effective production of alginate oligosaccharides from Laminaria japonica roots by Pseudoalteromonas agarivorans A3". *Microbial Cell Factories.* **22** : 179. 10.1186/s12934-023-02170-7.

[109] J. R. A. Avila, Z. Y. Kong, H.-Y. Lee, and J. Sunarso. (2021). "Advancements in Optimization and Control Techniques for Intensifying Processes". *Processes.* **9** (12): 2150. 10.3390/pr9122150.

[110] M. Yazdani, M. Ebrahimi-Nik, A. Heidari, and M. H. Abbaspour-Fard. (2019). "Improvement of biogas production from slaughterhouse wastewater using biosynthesized iron nanoparticles from water treatment sludge". *Renewable Energy.* **135** : 496-501. 10.1016/j.renene.2018.12.019.

[111] T. Ahmad, K. Ahmad, and M. Alam. (2016). "Sustainable management of water treatment sludge through 3'R' concept". *Journal of Cleaner Production.* **124** : 1-13. 10.1016/j.jclepro.2016.02.073.

[112] M. E. G. Boscov, J. K. T. , and E. L. T. Montalvan. (2021). "Beneficial Use of Water Treatment Sludge in Geotechnical Applications as a Sustainable Alternative to Preserve Natural Soils". *Sustainability.* **13** (17): 9848. 10.3390/su13179848.

[113] A. E. Nilsson, K. Bergman, L. P. G. Barrio, E. M. Cabral, and B. K. Tiwari. (2022). "Life cycle assessment of a seaweed-based biorefinery concept for production of food, materials, and energy". *Algal Research.* **65** : 102725. 10.1016/j.algal.2022.102725.

[114] M. Hashemi, S. Mirmohamadsadeghi, B. Khoshnevisan, Á. Galán-Martín, J. F. M. Denayer, and K. Karimi. (2025). "Life cycle assessment of bioenergy and value-added biochemical production from Nizimudinia zanardini brown macroalgae". *Science of the Total Environment.* **976** : 179225. 10.1016/j.scitotenv.2025.179225.

[115] A. Mohammed, K. Ward, K.-Y. Lee, and V. Dupont. (2023). "The environmental impact and economic feasibility assessment of composite calcium alginate bioplastics derived from Sargassum". *Green Chemistry.* **25** : 5501-5516. 10.1039/D3GC01019H.

[116] E. Nishikawa, M. G. C. d. Silva, and M. G. A. Vieira. (2018). "Cadmium biosorption by alginate extraction waste and process overview in Life Cycle Assessment context". *Journal of Cleaner Production.* **178** : 166-175. 10.1016/j.jclepro.2018.01.025.

[117] S. Radovic, M. T. Sekulic, B. Agarski, S. Pap, D. Vukelic, I. Budak, and J. Prodanovic. (2023). "Life cycle assessment of new bio-based coagulant production for sustainable wastewater treatment". *International Journal of Environmental Science and Technology.* **20** : 7433-7462. 10.1007/s13762-022-04440-0.

[118] S. Cojbasic, B. Agarski, D. Vukelic, M. T. Sekulic, S. Pap, M. Perovic, and J. Prodanovic. (2025). "Life cycle assessment of nature-based coagulant production: Light and dark sides of the freeze-drying process". *Industrial Crops and Products.* **226** : 120699. 10.1016/j.indcrop.2025.120699.