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Production, Characterization, and Application of the Biopolymer Alginate in the Food and Pharmaceutical Sectors: A Review

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ABSTRACT

Alginate, a naturally occurring polysaccharide isolated mainly from the cell walls of brown algae (Phaeophyceae), has attracted sustained research interest for its gelling, thickening, and stabilizing properties. However, the available literature on alginate remains scattered across disciplines, limiting its usefulness to researchers and industry. This review consolidates current knowledge on the production, structural characterization, and applications of alginate, with particular emphasis on the food and pharmaceutical sectors. Alginate can be obtained from brown algae or from bacterial fermentation, notably by *Pseudomonas* species and *Azotobacter vinelandii*, and its fine structure is routinely resolved using simple biochemical assays alongside spectroscopic and chromatographic techniques. In food systems, alginate functions as an emulsifier, stabilizer, and texture modifier; its antioxidant activity and capacity to encapsulate cells, DNA, nutrients, and microorganisms support the controlled release of flavours, minerals, and bioactive compounds. In pharmaceutical applications, alginate regulates the viscosity and stability of formulations and is used in wound-healing gels, dental impression materials, heavy-metal chelation, tissue engineering, controlled drug delivery, 3D bioprinting, and cell immobilization. Collectively, the evidence reviewed here confirms alginate as a versatile, biocompatible biopolymer of substantial and expanding industrial relevance.

Keywords: Alginate, Bacterial Culture, Biopolymer, Brown Algae, Drug Delivery, Food Packaging

INTRODUCTION

Alginate, a naturally occurring polymer mainly isolated from the cell walls of brown algae (Phaeophyceae), was first described in 1881 by the British chemist E.C.C. Stanford (Bouzenad et al. 2025). It is composed of two monomeric units, α-L-guluronic acid (G) and β-D-mannuronic acid (M), joined by 1→4 glycosidic linkages; brown algae such as *Ascophyllum*, *Macrocystis*, and *Laminaria* are particularly rich in these monomers (Garcia-Vaquero et al. 2017). Beyond brown algae, several bacteria including *Pseudomonas* species and *Azotobacter vinelandii* also produce alginate (Bouzenad et al. 2025).

Alginates are valuable in the food and pharmaceutical industries because of their gelling, thickening, and stabilizing properties (Bouzenad et al. 2025). In food systems they act as emulsifiers, stabilizers, and texture modifiers, improving product consistency and quality; in pharmaceutical formulations they regulate viscosity and stability, enhancing efficacy and usability (Gheorghita Puscaselu et al. 2020). Commercially, an estimated 30,000 metric tons of alginate are produced worldwide each year, with six countries China, the United States, the United Kingdom, Japan, Chile, and Germany accounting for the majority of this production (Bouzenad et al. 2025).

Alginate's physicochemical properties make it valuable for numerous commercial applications. In the presence of divalent ions such as calcium, it forms stable gels and is biocompatible, non-toxic, and biodegradable, properties that have driven its adoption across many industries (Ahmed 2019). It is also an effective food thickener and stabilizer because of its capacity to form viscous films and gels even at low concentrations (Benjamin et al. 2018). By varying the ratio of its β-D-mannuronic acid (M) and α-L-guluronic acid (G) blocks, alginate can be tailored for specific applications, including improved mechanical strength or better control of moisture and gas permeability, which broadens its usefulness across industrial applications (Bouzenad et al. 2025).

Alginate is also widely used in biomedicine for tissue engineering, controlled drug delivery, and wound healing (Bouzenad et al. 2025). Its exceptional biocompatibility and capacity to form three-dimensional gel structures create favourable conditions for cell encapsulation, controlled drug release, and tissue regeneration (Bouzenad et al. 2025), making it a versatile biomaterial for therapeutic and regenerative medicine.

Despite this versatility, the brittleness and stiffness of pure alginate films limit their practical use, so plasticizers and other additives are typically incorporated to overcome these limitations (Tong et al. 2023). Such additives increase stretchability and flexibility by lowering the glass transition temperature (Tg) of alginate, improving its suitability for food packaging (Tong et al. 2023). Antimicrobial compounds, antioxidants, and other active agents can further be incorporated into alginate films to extend shelf life and ensure food safety by limiting oxidation and microbial growth (Gheorghita Puscaselu et al. 2020). Alginate films are therefore a flexible and effective option for active food packaging (Gheorghita Puscaselu et al. 2020).

Although prior research highlights alginate's promise across a range of applications, the available literature remains dispersed across many sources, limiting its accessibility to researchers and industry alike. A systematic synthesis of this knowledge base would improve understanding, support further innovation, and provide a foundation for future studies and applications. This review therefore provides a comprehensive account of the production, characterization, and applications of alginate in the food and pharmaceutical sectors, highlighting recent developments while summarizing its principal benefits and uses.

MATERIALS AND METHODS

Methodological Approach

This is a narrative (non-systematic) literature review synthesizing published evidence on the production, characterization, and application of alginate; it does not follow a formal systematic-review protocol, and no review protocol was pre-registered.

Databases Searched

Google Scholar, PubMed, Scopus and Web of Science were searched between 20th of February, to 30th of March, 2026. These databases were selected for their high level content of published literature and easy retrieval of published literature.

Search Strategy

The principal researcher conducted the search alone; the PRESS checklist was not used for peer assessment of the search strategy, and this limitation is acknowledged. The search strategy involved combinations of the terms "alginate," "biopolymer," "brown algae," "bacterial culture," "food packaging," and "drug delivery," joined with the Boolean operators AND/OR (for example, "alginate" AND "food packaging"; "alginate" AND "drug delivery"). These terms correspond to the core themes and keywords of this review.

Inclusion/Exclusion Criteria

Articles published between 2016 and 2025, reflecting an emphasis on recent findings alongside a small number of earlier foundational sources. Articles were included if they were peer-reviewed journal articles, published in English, directly addressed the production, or structural characterization, or food or pharmaceutical application of alginate. Records were excluded if they are book chapters, or institutional reports, the full text could not be accessed, if alginate was not a substantive focus of the work (for example, articles concerned primarily with other biopolymers or exopolysaccharides), or if a record duplicated one already retrieved from another database.

Selection Process

Following the search, every record that was found was imported into Microsoft Excel to be screened and duplicates removed. Title screening, abstract screening, and full-text screening were all part of the three-phase selection procedure. The entire texts of retained records were then read after titles and abstracts were examined for subject relevance. The lead author independently carried out the whole screening process; neither inter-reviewer validation nor calibration activities were carried out. Therefore, any doubts about inclusion were cleared up by reviewing the inclusion criteria and considering the objectives of the study. This is acknowledged as a study limitation.

Result Synthesis

Data on alginate or production route, extraction and characterization method, and reported application were extracted into Microsoft Excel and organized thematically to support result synthesis. In total, 89 sources met these criteria and are cited in this review.

RESULTS AND DISCUSSION

Production Of Biopolymer Alginate

Alginate Production from Brown Algae

Commercial brown algae production began in California in 1929 and spread to Japan and several European countries by 1939 (Hurtado et al. 2022). Global seaweed production today shows marked regional imbalance: 49 countries and territories contribute to the world's 35.8 million tonnes of seaweed production, with Asia accounting for 97% of the total, led by China, Indonesia, the Republic of Korea, and the Philippines (Food and Agriculture Organization 2021). Chile is the leading producer in the Americas, on par with Japan, while France and Norway are the two largest producers in Europe, though their production rates are eight and three times lower than Japan's, respectively (Food and Agriculture Organization 2021). Brown seaweed, the principal source of alginate, is produced mainly in the United States, Norway, China, Canada, France, and Japan (Capuzzo and McKie 2016; Peteiro 2018). One advantage of producing alginate from brown algae is that most alginophytes yield substantial amounts of the polymer while growing on shallow, rocky shores (Quinn et al. 2018).

Alginate occurs in algae generally, and in brown algae in particular, primarily within the cell wall (Olatunji 2020); it is extracted using methods such as centrifugation, pH adjustment, and precipitation (Hurtado et al. 2022). Kane et al. (2016) reported an average alginate yield of 44.32% from brown algae. Notably, most of the more than 200 commercially available alginate grades are derived from wild brown seaweed (Hurtado et al. 2022). *Macrocystis pyrifera* is among the most important alginate-producing brown algae species; from an industrial perspective, *Ascophyllum nodosum*, *Macrocystis pyrifera*, and *Laminaria hyperborea* are the most significant (Peteiro 2018). Free-living gametophytes are cultured in the laboratory because they offer advantages for genetic selection, clone generation, and large-scale production (Peteiro 2018). The relative molecular mass of alginate ranges from 32 to 400 kg/mol, with algal species and age being the main sources of this heterogeneity (Hurtado et al. 2022).

Alginate Production from Bacterial Culture

Although first discovered in marine macroalgae, alginate is also produced by certain bacteria and forms a crucial part of the bacterial biofilm associated with lung disease (Hurtado et al. 2022). The most important bacterial producers of alginate are *Pseudomonas aeruginosa* and *Azotobacter vinelandii*, which secrete large quantities of the biopolymer as an extracellular product of their biofilm (Hurtado et al. 2022). Alginate is a major structural component of the *P. aeruginosa* biofilm, while *A. vinelandii* produces alginate with high G-block and low M-block content to enhance persistence in cysts. In these bacteria, the PMI-GMP isomerase enzyme participates in both early and late stages of alginate synthesis, and a number of genes govern the correct function of alginate polymerase (Hurtado et al. 2022).

Notably, some of the genes involved encode proteins that are not directly involved in alginate synthesis (Hurtado et al. 2022). Alginate itself stimulates further alginate production through a positive feedback loop at the gene promoter of the biosynthetic pathway, and these genes may be exploited for molecular engineering (Hurtado et al. 2022). Mannuronan C-5 epimerase, an enzyme that generates stereospecific epimers, regulates the composition of the alginate matrix; acetylation and epimerization occur during translocation to the periplasmic region and can chemically alter alginate. Genetic and protein engineering approaches, informed by bacterial genetics, can therefore be used to produce tailored bacterial alginates (Hurtado et al. 2022). Because the glycosidic product is acetylated at carbon positions 2 and 3, alginates derived from bacterial culture interact more strongly with water than those derived from algae (Hurtado et al. 2022). Up to 24 genes have been implicated in alginate synthesis in *P. aeruginosa*, most located on the bacterial chromosome; none has so far been found on a plasmid.

The quality of bacterial alginate is generally considered superior to that of algal alginate, and its properties and biological activities have been extensively investigated (Gonzalez-Pujana et al. 2018; Dhamecha et al. 2019). However, bacterial alginate production has notable drawbacks relative to extraction from brown algae: production costs are considerably higher (Adeyeye et al. 2019), mucoid strains of *P. aeruginosa* frequently lose the capacity to produce alginate under laboratory culture, and the enzymes alginate lyase and epimerase interfere with extraction (Hurtado et al. 2022).

Industrial Production of Alginate

Industrial alginate production has traditionally relied on extraction from brown algae; however, microbial production using *A. vinelandii* and *Pseudomonas* species is attracting growing industrial interest. These bacteria produce alginate as an extracellular polymer whose properties can be tailored by adjusting culture conditions. Urtuvia et al. (2017) note that this biotechnological approach offers a controllable, scalable, and sustainable alternative to conventional industrial production, ensuring consistent supply and quality. Its ability to generate alginates with stable, defined properties while using inexpensive carbon sources such as carbon-rich industrial waste makes microbial production increasingly attractive (Wang et al. 2023). Genetic modifications that improve access to fructose-6-phosphate and cellular energy management, both critical to alginate biosynthesis, make bacterial strains such as *Pseudomonas fluorescens* promising candidates for more sustainable industrial production (Maleki et al. 2017). This approach fits within the broader framework of biomass valorization, and the recovery of bioactive by-products such as fucoidans and polyphenols from alginate-manufacturing waste offers further opportunities to improve the sustainability of industrial operations without major changes to existing processes (Bojorges et al. 2022). Overall, microbial alginate synthesis presents a viable route toward more economical and environmentally sustainable biopolymer production.

Characterization Of Biopolymer Alginate

Sodium alginate (SA), also referred to as alginic acid, belongs to the class of polymeric sugars (Tavassoli-Kafrani et al. 2016). It is a linear polysaccharide composed of two acid monomers, α-L-guluronic acid (G) and β-D-mannuronic acid (M), arranged in blocks at varying M/G ratios and joined by 1→4 O-glycosidic bonds (Hurtado et al. 2022). These two monomers occur in varying sequence patterns along the alginate chain (Hurtado et al. 2022). The chemical structure of a short alginate chain, together with its constituent M- and G-blocks, is shown in Figure 1.

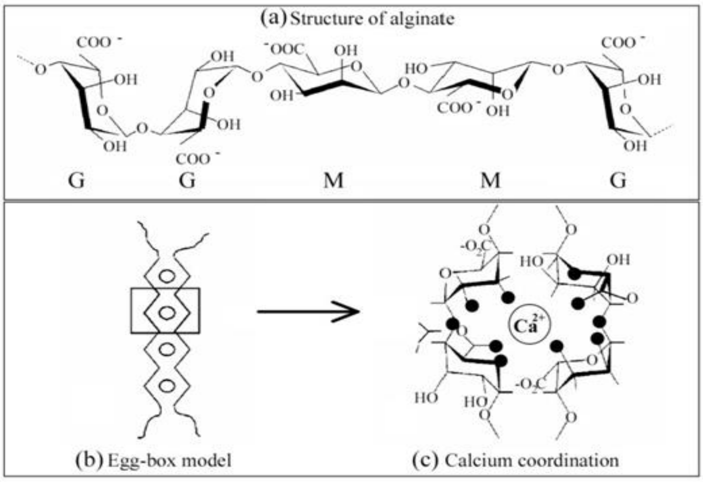

Figure 1. Chemical structure of alginate and alginate gelling: (a) blocks of α-(1→4)-L-guluronic acid (G) and β-(1→4)-D-mannuronic acid (M); (b) the egg-box model; and (c) a pair of guluronate chains in calcium alginate junction zones depicting calcium coordination. Dark circles represent the oxygen atoms involved in calcium-ion coordination. **Source:** Hurtado et al. (2022).

Structural characterization of alginate relies on both simple biochemical assays and more sophisticated techniques, including spectroscopy and chromatography, to resolve its fine structure. Chemical assays are used to quantify both sugar content (total sugar, neutral sugar, and uronic acids) and non-sugar impurities (phenolic compounds, proteins, and sulfated groups) co-extracted with seaweed alginates. The M/G ratio of alginate, following complete acid hydrolysis with formic acid (90% v/v) or trifluoroacetic acid (2 M, 90 min, 120°C), can be determined using high-performance anion-exchange chromatography with pulsed amperometric detection (HPAEC-PAD) or gas chromatography coupled with mass spectrometry and electron ionization (GC/MS-EI), respectively (Hentati et al. 2018).

^{1}H NMR spectroscopy is the primary technique used to examine alginate structure and composition (Sari-Chmayssem et al. 2016) (Figure 2). Using this technique, Abka-khajouei et al. (2022) examined five brown algae species from the Egyptian Red Sea coast — *Sirophysalis trinodis* (formerly *Cystophyllum trinode*), *Polycladia myrica* (formerly *Cystoseira myrica*), *Sargassum dentifolium*, *Sargassum asperifolium*, and *Sargassum latifolium* — and found a homopolymeric block-type structure with guluronic acid (G) content exceeding mannuronic acid (M) content. Alginate is typically present in seawater as an insoluble salt of the cations it encounters — primarily calcium, magnesium, and sodium — undergoing rapid ion exchange. Extraction can therefore be understood as a two-stage process: the insoluble alginate salt is first converted to a soluble form, after which the resulting soluble glycuronan diffuses into solution (Abka-khajouei et al. 2022).

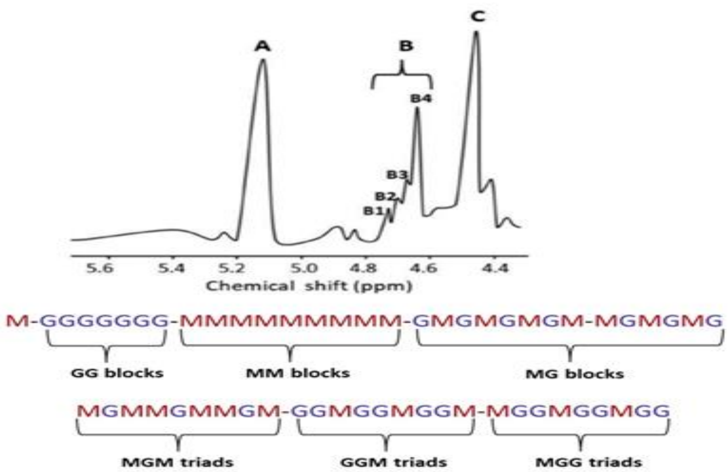

Figure 2. Possible sequences of L-guluronic (G) and D-mannuronic (M) acid residues in alginate. The H-5 signal of the central G residue in MGM, GGM, and MGG triads appears at 4.70–4.75 ppm (B2), 4.74–4.78 ppm (B1),

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and 4.42–4.44 ppm, respectively. The H-1 signal of M appears at 4.66–4.68 ppm for neighbouring M residues (B4, MM) and 4.68–4.70 ppm for neighbouring G residues (B3, MG). **Source:** Abka-khajouei et al. (2022).

Alginates are primarily characterized by molecular mass (Mw, Mn), polydispersity index (Mw/Mn), macromolecular parameters such as intrinsic viscosity ([η]), critical concentration (C*), radius of gyration (Rg), and hydrodynamic radius (Rh), as well as by M/G ratio and the number and length of monad (G, M), diad (GG, MM, GM/MG), and triad (MMG, GGM, MGM) sequences, whether free in solution or in the presence of monovalent (K^+, Na^+) or divalent (Ca^{2+}) cations (Hentati et al. 2018). Depending on the source organism, alginates may show a sequential arrangement (repeating GGGG or MMMM blocks), an alternating arrangement (GMGMGMGM), or a random arrangement of G and M residues (Fernando et al. 2020).

The linear, flexible structure of alginate is characterized by a steric barrier surrounding the carboxyl groups, where G-blocks form folded, rigid structures (Abka-khajouei et al. 2022). Alginate is marketed commercially as the sodium, potassium, or ammonium salt, and commercial preparations typically have a molecular weight between 60,000 and 700,000 Da, depending on the intended use (Ching et al. 2017).

Because alginate contains numerous free hydroxyl (–OH) and carboxyl (–COOH) groups, it can form intramolecular hydrogen bonds (Fernando et al. 2020). Alginate oligosaccharides (AOS) — oligomers of two to twenty-five monomer units — can be produced by biosynthesis, organic synthesis, or hydrolysis of glycosidic linkages (Liu et al. 2019), including depolymerization of alginate with H_2O_2, synthesis of a mannuronic acid pentamer via an orthogonal glycosylation strategy, and biosynthesis of AOS from glucose using *Pseudomonas mendocina* NK-01 under nitrogen limitation. Owing to their shorter chain length, AOS are more soluble than higher-molecular-weight alginates, and their increased biological activity has drawn considerable research interest. Reported bioactivities include immunomodulatory, antimicrobial, antioxidant, probiotic, antihypertensive, antidiabetic, antitumour, anticoagulant, photoprotective, and anti-hypoglycaemic effects, along with suppression of obesity and promotion of cell proliferation (Liu et al. 2019; Xing et al. 2020). AOS have also been used to regulate plant growth, as post-harvest treatments, as growth stimulants for plants and microorganisms, as nutritional supplements for pigs, poultry, and aquaculture species, and as cryoprotectants for frozen foods (Liu et al. 2019; Xing et al. 2020).

Application Of Biopolymer Alginate

Food Sector

General Application

In the form of films, alginate has shown considerable promise for biodegradable packaging (Hurtado et al. 2022); the biopolymer is also used in the paper and craft industries, aquaculture, and the food and beverage sector, including ice cream and beer production. In food applications, alginate is commonly used to modify rheology (thickening), water-binding capacity, emulsion stability, and film formation (Ching et al. 2017), and it extends the shelf life of products such as tomatoes (*Solanum lycopersicum*) (Abdel Aziz and Salama 2021), mushrooms (*Agaricus bisporus*) (Louis et al. 2021), shrimp (Baek et al. 2021), turkey fillet (Kazemeini et al. 2021), chicken thigh meat (Molayi et al. 2018), low-fat cut cheese (Artiga-Artigas et al. 2017), and meat (Senturk Parreidt et al. 2018). Because of its thickening and gelling properties, it is also used in sauces, jam, marmalade, syrups, ice cream toppings, fruit pies, and animal feed (Hurtado et al. 2022).

Small quantities of propylene glycol alginate are used in ice cream production, giving a softer texture, fewer ice crystals, and a more pleasant mouthfeel. Alginate is also used to stabilize fruit drinks and beer, and it benefits water-in-oil emulsions such as mayonnaise and salad dressing (Abka-khajouei et al. 2022). The meat industry is exploring calcium alginate structures as an alternative to animal-based natural casings; a 2015 study found that alginate coatings could be a suitable substitute for natural casings in fermented sausages stored at 12°C (Abka-khajouei et al. 2022). The distribution of monomers along the chain and the overall uronic acid composition (M/G ratio) strongly influence the physiological and rheological properties of alginate and, in turn, its performance as a stabilizer, thickener, gelling agent, or pharmaceutical excipient (Abka-khajouei et al. 2022).

Alginate is valued in food applications for its high viscosity and low water solubility, and its antioxidant properties help protect food from oxidative damage caused by free radicals (Abka-khajouei et al. 2022). Its antioxidant efficacy depends on structural features such as molecular weight, monosaccharide composition, and glycosidic branching. Both molecular weight and M/G ratio strongly influence alginate's capacity to scavenge free radicals: low-molecular-weight polysaccharides are thought to offer more reducing hydroxyl groups per unit mass, while a higher proportion of G residues enhances antioxidant activity because diaxial bonding within G-blocks restricts rotation around the glycosidic linkage. This restricted rotation increases G-block flexibility, which in turn affects the availability of hydroxyl groups and the hydrogen-donating capacity of sodium alginate (Abka-khajouei et al. 2022).

Alginate can also inhibit free-radical chain reactions, protect NT2 neurons from H_2O_2-induced neurotoxicity, and reduce lipid peroxidation of phosphatidylcholine and linoleate liposomes (Khajouei et al. 2018). In a study of sodium alginate from the Tunisian seaweed *Gongolaria barbata* (formerly *Cystoseira barbata*), Benslima et al. (2021) reported 37% mannuronic and 63% guluronic acid content; this alginate was more stable at acidic pH and less sensitive to temperature change, and it provided moderate antioxidant activity together with notable protection against DNA damage, supporting its potential use as a natural material in the food and pharmaceutical industries. Alginate can also encapsulate live probiotic cells for use in food products and in the digestive tract (Petzold et al. 2019), with microencapsulation protecting bacterial viability during storage (Gheorghita Puscaselu et al. 2020). It is used at very low concentrations in milk chocolate as a thickener, emulsifier, and stabilizer, and as a component of functional foods containing probiotics and prebiotics (Petzold et al. 2019).

Different Kinds of Gels

Hydrocolloid gel particles are used extensively in the culinary, chemical, and pharmaceutical industries. Alginate is among the most widely used gelling agents today because of its good biocompatibility, non-toxicity, biodegradability, low cost, and ease of manufacture (Ching et al. 2017). It is also well suited to encapsulation applications, protecting cells, DNA, nutrients, and microorganisms, and enabling the gradual release of flavours, minerals, and medications through gel-particle encapsulation (Zbilenler et al. 2020). Notably, the presence of active compounds within Ca-alginate gel particles does not appear to compromise flavour release on consumption (Bi et al. 2022).

Alginate is frequently used in the food industry to encapsulate active ingredients because it forms an ionic gel in the presence of multivalent cations. It binds divalent cations with high selectivity, following the affinity order Mn < Zn, Ni, Co < Fe < Ca < Sr < Ba < Cd < Cu < Pb, which depends directly on the G content of the alginate (Zbilenler et al. 2020). This selectivity arises because G residues preferentially bind divalent cations during gelation, dimerizing to form a tightly bonded polymer network known as the "egg-box" junction structure (Ching et al. 2017). Alginate gels with high M content tend to be weak, elastic, and freeze-thaw stable, whereas gels with high G content are stronger, more brittle, and thermally stable (Xu et al. 2016; Ching et al. 2017). Calcium is the most commonly used ion for practical Ca-alginate gel formation, given its favourable toxicity profile relative to other divalent cations.

Ca-alginate gel particles can be produced by either internal or external gelation, which differ primarily in how Ca^{2+} is introduced into the alginate polymer (Ching et al. 2017). In internal gelation, alginate exposure to Ca^{2+} is controlled to distribute the ion evenly throughout the solution, so that gelation proceeds synchronously and produces a homogeneous hydrogel. A sodium alginate solution is typically first mixed with an insoluble calcium salt such as $CaCO_3$ or $CaSO_4$ and extruded into oil (Bi et al. 2022); the mixture is then acidified either directly with glacial acetic acid (Bi et al. 2022) or in a controlled manner using D-glucono-δ-lactone (Chen et al. 2021; Li et al. 2021) — to release Ca^{2+} from the salt. In external gelation, Ca^{2+} diffuses into the alginate from a region of higher concentration outside the gel; because Ca^{2+} content is highest at the outer layer, gelation occurs rapidly there, producing an inhomogeneous gel with pronounced Ca^{2+} and alginate gradients that diminish toward the core (Ching et al. 2017).

Bi et al. (2022) compared Ca-alginate gels produced by these two methods in terms of structure, physicochemical properties, and diffusion behaviour, finding that gels produced by internal gelation had larger pores and a looser structure than those produced by external gelation, resulting in faster diffusion of vitamin B12 through internally gelled particles. The study also found that: (i) Ca^{2+} concentration was the critical determinant of gel formation; (ii) weight and volume loss resulted from water removal; (iii) Na^{+} competed with Ca^{2+} for binding sites; and (iv) pH controlled gel formation by governing calcium complexation and alginate dissociation in externally gelled particles (Bi et al. 2022). Temperature also influences gel formation: Jeong et al. (2020) found that reducing gelation temperature slows Ca^{2+} diffusion into Ca-alginate gel particles, increasing their rupture strength and yielding a more regular internal structure, and water loss during thermal treatment promotes a thicker, more porous structure that enhances fracture strength (Kim et al. 2019). However, dried alginate gel particles tend to harden, which limits their application; glycerol has been shown to improve the tolerance of gel particles and stabilize the gel network by forming hydrogen bonds with alginate (Wang et al. 2021). A further limitation of Ca-alginate gels is their instability in the presence of calcium chelators such as lactate, carbonate, phosphate, and citrate (Ching et al. 2017).

Diffusion studies show that solute movement through Ca-alginate gel particles with molecular weight below 20,000 Da is largely unaffected by alginate or Ca^{2+} concentration (Bi et al. 2022). By contrast, the diffusion coefficient of vitamin B12 decreased with increasing alginate concentration and increased with decreasing calcium concentration during release studies (Bi et al. 2022). Lopez-Sanchez et al. (2018) further found that Ca-alginate gel particles with high sugar content (glucose:fructose > 60%) formed open, loosely connected aggregation networks in simulated gastric fluid, likely because high sugar levels as a co-solute reduce network connectedness and promote alginate chain extension. Sugar release from these particles followed a diffusion-driven mechanism similar to that observed at lower sugar content (< 30% w/w), suggesting that Ca-alginate gel particles can carry low-molecular-weight sugars without impeding their release in the digestive tract (Lopez-Sanchez et al. 2018).

Ca-alginate gel particles can enhance the functionality and stability of plant polyphenols in food products. Encapsulation of aqueous *Thymus serpyllum* extracts within Ca-alginate gel particles successfully prevented degradation of the active ingredients, with no evidence of chemical interaction between the alginate and the encapsulated compounds (Bi et al. 2022), achieving encapsulation efficiencies of up to 80%. Similarly, Najafi-Soulari et al. (2016) found that Ca-alginate gel particles preserved the antioxidant activity of lemon balm extracts without chemical interaction, confirming the suitability of alginate for loading natural antioxidants.

Kim et al. (2016) produced catechin-loaded Ca-alginate gel particles by emulsion gelation using sunflower seed oil, achieving sustained catechin release under acidic conditions an efficient delivery system, although one that favours release in the stomach over the intestine. Probiotics such as *Lactobacillus rhamnosus* and *Lactobacillus acidophilus* have also been encapsulated in Ca-alginate gel particles using an impinging aerosol technique, producing particles below the sensory detection threshold that offer some protection against gastric acidity and bile (Bi et al. 2022). Using the dripping method, Ca-alginate gel particles loaded with liquid smoke flavouring achieved a loading capacity exceeding 96% and released volatile compounds progressively on heating (Bi et al. 2022); D-limonene, the principal flavour component of citrus oil, has similarly been immobilized in Ca-alginate gel particles to improve its thermal stability. To minimize the powdery or grainy texture perceptible in foods such as yoghurt and ice cream, gel particles used in food applications are typically kept below 30 µm in diameter, and most reported Ca-alginate gel particles for food use fall within this range (Bi et al. 2022).

Alginate carries a negative charge across a broad pH range, reflecting the dissociation constants (pKa) of 3.38 and 3.65 for the M and G residues, respectively; the alginate solution can gel spontaneously once the pH falls below these values (Bi et al. 2022). The rate of pH decrease determines the type of colloid formed: rapid acidification causes alginate to precipitate as an aggregate, whereas gradual, sustained acidification produces a continuous bulk gel (Bi et al. 2022). Unlike ionic gels, alginate acid gels are stabilized by hydrogen bonds, with M residues also contributing to gel formation; in both cases, gel strength correlates with G-residue content (Bi et al. 2022). The low pH required for acid-gel formation limits its use in food applications (Ching et al. 2017), although it has found use as an antacid for treating heartburn and gastric reflux (Foocharoen et al. 2017).

Ca-alginate gels are frequently used to form core–shell structures and are pH-sensitive, but they remain unstable in the digestive tract; consequently, most nutrients or active ingredients carried in Ca-alginate gels may be released prematurely in the stomach, exposing them to harsh acidic conditions and compromising delivery to the intestine. To improve colloidal performance, researchers have incorporated proteins and other polysaccharides alongside alginate in gel formulations. Lin et al. (2020) found that adding soy protein isolate to Ca-alginate gel-based emulsions improved morphology and elasticity while reducing shrinkage and water loss; adding low concentrations of soy-protein-isolate-stabilized emulsion to alginate solution (rather than the reverse) produced a more stable emulsion under gentle stirring (Lin et al. 2021).

Similar research shows that whey protein isolate and casein can also improve the properties of Ca-alginate-based emulsion gels (Leon et al. 2018; Li et al. 2021), although the viscosity of Ca-alginate gel-based emulsion was greater following addition of whey protein isolate than following addition of soy protein isolate. Droplet flocculation and particle size were both smaller in emulsions containing whey protein isolate than in those containing soy protein isolate (Lin et al. 2020), and whey protein isolate like soy protein isolate reduced water loss from the emulsion during the gel phase (Lin et al. 2020). Notably, the shrinkage rate and rate of change in Young's modulus increased in emulsions containing whey or soy protein isolate during simulated gastric digestion, while lycopene release was delayed during simulated intestinal digestion (Lin et al. 2020). To protect probiotics, improve storage and lyophilization stability, and achieve sustained release in the gastrointestinal tract, Deng et al. (2021) developed a novel core–shell structure using sporopollenin exine capsules as the core and a Ca-alginate/carboxymethylpachymaran (CMP) gel as the shell.

The stability of an active ingredient or nutrient incorporated into alginate-based emulsion gels can also be enhanced by including protein and other components. Chen et al. (2021) found that bioactive compounds coated with oil droplets are more likely to be retained during heating, and that emulsion gels can protect both lipophilic and hydrophilic bioactive molecules; simultaneous encapsulation of β-carotene and epigallocatechin gallate in whey-protein-isolate/calcium-alginate emulsion gels enhanced their chemical stability and produced synergistic effects (Chen et al. 2021). Cross-linking zein with transglutaminase and alginate with calcium ions produced a double-cross-linked emulsion gel with a dense mesh structure and strong viscoelasticity; when co-loaded with polyphenols (resveratrol and curcumin), double-cross-linked emulsion gels showed greater photostability and bio-accessibility than single-cross-linked gels (Yan et al. 2021).

Calcium alginate gel particles can also be used to produce low-fat mayonnaise and similar emulsions (Li et al. 2020). Using alginate and konjac glucomannan, Yang et al. (2020a) created a thixotropic, viscoelastic emulsion gel with good freeze–thaw and heat stability, showing no oil-droplet coalescence after freezing at −18°C for 24 hours or heating at 100°C for 30 minutes; this konjac glucomannan/Ca-alginate emulsion gel system may serve as a model for low-fat mayonnaise-type food emulsions (Yang et al. 2020a). Yang et al. (2020b) also produced oil-in-water emulsions by electrostatically complexing alginate with egg yolk proteins at acidic pH (< 5.0); the resulting emulsion gels had viscoelasticity and thixotropy comparable to full-fat (75% oil) mayonnaise, with vinegar added to improve sensory acceptability (Yang et al. 2020b). Findings such as these may help reduce dietary fat intake and, in turn, the prevalence of associated chronic diseases.

Film Packaging

A newer class of environmentally friendly, biodegradable film packaging is produced mainly from extracts of fruit and vegetable processing by-products, adding value to these residues while reducing waste and environmental impact (Li et al. 2021). Alginate's colloidal properties thickening, stabilization, suspension, film formation, gelation, and emulsion stabilization make its films robust and resistant to oil and grease (Umaraw and Verma 2017), although their hydrophilicity limits water resistance (Bi et al. 2022). Alginate is therefore commonly blended with other biopolymers to improve the mechanical properties of these films.

Ismillayli et al. (2020) reported that the carboxyl groups of alginate can interact electrostatically with the ammonium groups of chitosan; compared with alginate or chitosan films alone, alginate–chitosan films of equal thickness showed greater tensile strength and resistance to pH fluctuation, as well as strong antibacterial activity against *Escherichia coli* and *Staphylococcus aureus*. Alginate–chitosan coatings have also proved effective for post-harvest preservation of figs, maintaining organoleptic quality, sensory properties, and bioactive compound content by modifying the internal atmosphere of the fruit during cold storage (Reyes-Avalos et al. 2016, 2019).

Composite alginate films combined with other polymers or bioactive compounds retain good mechanical properties while gaining antibacterial and antioxidant activity. For example, a gelatin–alginate film containing

1.5% oregano essential oil inhibited the growth of lactic acid bacteria, *Pseudomonas* species, and Enterobacteriaceae on rainbow trout (*Oncorhynchus mykiss*) slices (Bi et al. 2022), while the addition of tea polyphenols to gelatin–alginate film improved both mechanical properties and antioxidant activity (Dou et al. 2018). Adding vitamin C to alginate-based edible film reduced tensile strength but improved stability, allowing refrigerated storage in the dark for up to five months (Bi et al. 2022).

A composite film of citrus pectin and alginate showed good tensile strength and elongation at break; cross-linking with calcium chloride reduced water solubility and increased thermal stability, and the addition of pterostilbene as an antioxidant reduced tensile strength and elongation at break while improving water and oxidation resistance, supporting its potential as an antioxidant packaging material for fruit and vegetable preservation (Li et al. 2021). Similarly, adding epigallocatechin gallate to alginate–carboxymethyl cellulose edible films increased tensile strength, decreased elongation at break, and enhanced antioxidant activity in fatty foods (Ruan et al. 2019).

Alginate films containing lemongrass oil and glycerol, acting as a natural antibacterial agent and plasticizer respectively, effectively inhibited *Escherichia coli* growth (Bi et al. 2022). The mechanical and antibacterial properties of alginate-based edible films were similarly enhanced by the addition of silver nanoparticles, achieving growth-inhibition rates above 79% across all tested strains (Martínez-Molina et al. 2021). Essential oils (Zhu et al. 2019), mulberry (*Morus australis*) leaf extract (Kuan et al. 2020), and hawthorn berry (*Crataegus pinnatifida*) extract (Lim et al. 2021) have each been shown to improve mechanical properties, antibacterial activity, and sensory qualities when added to alginate-based edible films (Mahcene et al. 2020). Increasing capsaicin content in alginate–pullulan films increased tensile strength, permeability, and surface contact angle, while reducing light transmittance, elongation at break, and moisture content (Zhang et al. 2018); such films have also shown good protective performance on apples and strong antibacterial activity against *Staphylococcus aureus* and *Escherichia coli* (Zhang et al. 2018).

Because seaweed is alginate-rich, alginate-based films are relatively inexpensive to produce, and blending alginate with other polysaccharides can mitigate its otherwise poor water resistance. Incorporating specific active ingredients further confers antibacterial and antioxidant properties that extend food shelf life. AOS have seen limited use in edible film production to date, owing to their weak colloidal properties, but their strong biological activity suggests potential value in polysaccharide-based films for more targeted applications.

Pharmaceutical Sector

Alginate is an FDA-approved substance used in numerous medical applications, including gel-based wound-healing treatments and thickening/stabilizing agents for dental impression materials (Xu and Lam 2018), heavy-metal chelation (Borgiallo and Rojas 2019), tissue engineering (Kostenko et al. 2022), controlled drug delivery (Silva et al. 2016), 3D bioprinting (Axpe and Oyen 2016; Kang et al. 2016), prostheses and dental moulds (Hurtado et al. 2022), and cell immobilization (Hurtado et al. 2022). Because alginate hydrogels possess sufficient porosity for drug delivery, they can effectively encapsulate substances such as insulin and other enzymes for controlled release (Fabra et al. 2019). Pharmaceutical applications extend to food supplements, gastric reflux treatment, and cancer therapy (Ferreira et al. 2017; Baldassarre et al. 2020; Mirrahimi et al. 2020), and alginate can be combined with drugs such as ketoprofen for oral administration in colonic disease, providing anti-inflammatory benefits (Agüero et al. 2017).

Recent developments have explored alginate as a matrix for three-dimensional tissue culture, as an adjuvant for antibiotics, for cell transplantation in diabetes, and in alginate-based treatments for neurological disorders as well as antimicrobial and antiviral therapy (Szekalska et al. 2016). Its strong biocompatibility and biodegradability make alginate-based particles a key component of many drug-delivery systems, and its low cost, availability, and cell-gel transfer properties make it well suited to the production of particles and nanoparticles for varied applications (Lopes et al. 2017). At the nanoscale, alginate-based nanotechnology enables drug delivery with reduced side effects; the principal aims of this approach are to increase drug loading, reduce toxicity, and improve safety, therapeutic efficacy, and biocompatibility (Hasnain et al. 2020).

Polysaccharides derived from *Sargassum fusiforme* have been shown to substantially reduce triglyceride, low-density lipoprotein cholesterol, and total cholesterol levels in mice (Abka-khajouei et al. 2022), while crude extract of *Sargassum polycystum* significantly affects acetaminophen-induced hepatic enzyme metabolism and prevents severe hepatic lipid abnormalities (Abka-khajouei et al. 2022). Alginate is also used as a matrix for encapsulating and releasing cells and drugs; because it is non-toxic and FDA-approved, its microparticle form is used in antigen-release systems. *Sargassum vulgare* extract has demonstrated inhibitory activity against syncytium formation induced by human T-cell lymphotropic virus type 1 (HTLV-1), suggesting potential in infection prevention (Abka-khajouei et al. 2022). Alginate's anticoagulant activity further supports its use in biomedicine (Sari-Chmayssem et al. 2016), and alginate composites serve as controlled protein-delivery agents owing to their porosity and gelling capacity, as antiglycaemic dietary supplements owing to their antioxidant and antibacterial properties, and as vehicles for in vivo delivery of tissue-enhancing cells and proteins (Król et al. 2017; Jönsson et al. 2020).

Other Applications

Alginate's biocompatibility, biodegradability, and capacity to gel in the presence of polyvalent cations make it a distinctive material for medical applications (Abka-khajouei et al. 2022). Its exceptional cross-linking and adhesion properties make alginate microparticles well suited for colon-targeted drug delivery, offering a promising material for improving quality of life in patients with inflammatory bowel disease. Alginate is also used in combination with other polymers and in microcoating applications (Agüero et al. 2017), and alginate hydrogels derived from brown algae are used in three- and four-dimensional bioprinting for engineering bone, cartilage, neural, ear, cardiac, and corneal tissue, providing access to model organs for studying a range of diseases (Rastogi and Kandasubramanian 2019). Low-molecular-weight alginates have also been shown to help prevent diabetes, obesity, and hypercholesterolaemia (Sari-Chmayssem et al. 2016).

Reakasame and Boccaccini (2018) reported that oxidized alginate (OA) hydrogels are used in tissue engineering applications for soft tissues such as cartilage, bone, blood vessels, and corneas. Oxidation generates aldehyde groups in the oxidized monomer units and breaks C–C bonds, lowering the molecular weight of OA relative to unmodified alginate and, because the resulting aldehyde groups are susceptible to hydrolysis, accelerating biodegradation. Although OA has weaker mechanical properties than pure alginate and its aldehyde groups can be somewhat cytotoxic, these groups also enable covalent cross-linking with amine-containing components via Schiff-base reactions; covalent cross-linking consumes free aldehyde groups, improving both the gel's mechanical properties and OA's biocompatibility. By controlling the gel's chemical composition or degree of oxidation, OA-based hydrogels can therefore be tailored for a range of medical applications (Reakasame and Boccaccini 2018). Injectable alginate hydrogels and their composites have also been used for bone tissue regeneration (Hernández-González et al. 2020).

Bone is a complex tissue composed mainly of collagen and nanohydroxyapatite, and tissue-engineering approaches have been used to generate artificial bone since as early as 2015 (Abka-khajouei et al. 2022). As an anionic, biocompatible, gel-forming polymer, alginate is widely used in bone tissue engineering; composites explored to date include alginate–polymer blends (with PLGA, PEG, or chitosan), alginate–protein blends (with collagen or gelatin), alginate–ceramic, alginate–bioglass, alginate–biosilica, and RGD-peptide conjugates. These composites have demonstrated favourable porosity, mechanical strength, cell adhesion, biocompatibility, cell proliferation, alkaline phosphatase activity, mineralization, and osteogenic differentiation, supporting the use of alginate-based composite biomaterials in bone regeneration (Abka-khajouei et al. 2022).

Alginate has also been proposed as a substitute for polyelectrolyte membranes in low- to medium-temperature polymer electrolyte fuel cells, direct methanol fuel cells, polymer–alkali electrolyte fuel cells, and biofuel cells (Abka-khajouei et al. 2022). Its hydrophilicity allows ready modification to achieve properties such as low methanol permeability and proton conductivity comparable to Nafion membranes, and alginate-based polyelectrolyte complexes have consistently outperformed other modifications while remaining comparatively inexpensive to produce (Abka-khajouei et al. 2022).

Alginate is among the many polymers used across the food, pharmaceutical, and packaging industries. In medical science, electrospinning is used to produce non-woven nanoscale structures that combine biopolymers and natural materials with drugs (such as naproxen and sulfisoxazole) and antibacterial essential oils (such as tocopherol and eugenol); this technique enables encapsulation and controlled delivery of bioactive compounds from high-quality nanoscale materials, and alginate shows considerable promise among the materials investigated for electrospinning (Wróblewska-Krepsztul et al. 2019). Pollution of aquatic habitats by heavy and toxic metals from mining and industrial effluent remains a major environmental concern, and the treatment of contaminated effluent is a priority; adsorption is regarded as one of the most efficient and sustainable methods for removing persistent pollutants from the environment.

Alginate-based composites combining alginate gels with other polymers, natural or synthetic nanoparticles, and microorganisms are frequently used as inexpensive, highly effective adsorbents for removing heavy metals, industrial dyes, pesticides, antibiotics, and other contaminants from water and wastewater (Wang et al. 2019). Biosorption, a passive, non-metabolic process, uses natural biomass to chelate metal ions; brown *Sargassum* algae, for example, possess the mechanical, chemical, and adsorptive properties needed to bind metals such as Cd, Au, Cu, Fe, Ni, Pb, and Zn from contaminated waterways effectively, reversibly, and economically (Abka-khajouei et al. 2022).

Alginate is chiefly responsible for the heavy-metal biosorption capacity of these algae; the relative levels of guluronic and mannuronic acid, the block composition of the calcium alginate network, and overall alginate content are all critical to this process. The presence of G monomers in brown algae and purified alginates is particularly important, as it promotes effective divalent-ion binding (Abka-khajouei et al. 2022). Hydrogel alginates are accordingly used in wastewater treatment, in the food industry, and as adsorbents for heavy-metal removal from contaminated water (Fernando et al. 2020). Highly absorbent alginate-based hydrogels with good mechanical stability and viscoelastic properties are also used in wound dressings (Szekalska et al. 2016), and sodium alginate serves as a thickener, stabilizer, and gelling agent in the textile and paper industries (Abka-khajouei et al. 2022).

CONCLUSION

This review has synthesized current knowledge on the production, structural characterization, and application of the biopolymer alginate. Alginate can be obtained from brown algae or from bacterial fermentation, and its fine structure can be resolved through simple biochemical assays as well as spectroscopic, chromatographic, and ^{1}H NMR techniques. Its gelling, thickening, and stabilizing properties underpin extensive use in the food industry as an emulsifier, stabilizer, and texture modifier, and in pharmaceutical formulations as a viscosity- and stability-regulating agent, with further applications spanning wound care, drug delivery, tissue engineering, and heavy-metal remediation. Taken together, the evidence confirms alginate as a versatile, biocompatible, and increasingly important industrial biopolymer.

Limitations of the Study

Despite being a narrative review, this study did not provide contradictory results about the several themes that were highlighted, and there were limited discussions of the themes. The search procedure was carried out by only one researcher and not subjected to external scrutiny or evaluation, and the study did not adhere to a predetermined or complex search protocol. Additionally, the inclusion/exclusion criteria were not further examined, and there was no inter-reviewer or co-author validation of the article screening procedure.

Future Research

Future work should prioritize standardizing extraction and characterization protocols across studies, clarifying structure–function relationships across the M/G compositional range, and generating comparative techno-economic data on algal versus microbial alginate production to guide industrial scale-up.

Declarations

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Doughari J.H. conceptualized and designed the study. Mbahi M.A. carried out the literature search, screening of articles, result synthesis, and prepared the first draft of the manuscript. Both authors reviewed the first draft, made amendments, prepared the second draft, read and approved the final manuscript.

Authors' relationships and activities

The authors declare that their relationships and activities are professional and academic in nature, and that there is no bias affecting this work.

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