Chapter 15
Natural Polysaccharides: Novel Plant Growth Regulators

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15.1 Introduction

Crop production plays a critical role in an agricultural-based economy like India. The agriculture sector still decides the fate of 70% of its rural population (FAO 2015). Apart from cereal crops, India is a major exporter of crops with commercial standards. Presently, various innovative methods for crop enhancement are being sought to meet the rising demand of exponentially growing population. Fertilizers, PGRs, minerals and metal nanoparticles have proved their elicitor effect on various crops (Tripathi et al. 2016; Ahmad et al. 2019). However, their side effects and toxicity have always been a concern. Therefore, much recent research has been directed to explore some more sustainable and eco-friendly growth elicitors. Natural polysaccharides (NPs), besides being growth enhancers, are also antimicrobial, non-toxic, biocompatible and cheaper with no negligible side effects (Hu et al. 2005; Campo et al. 2009; Yan and Chen 2015). This makes NPs farmer-friendlier and a more sustainable option. Moreover, due to its greater biocompatibility, NPs legend with cell membrane and regulate membrane permeability. Various sources have asserted their eliciting effect on various crops with ample data to support (El-Mohdy 2017; Rabêlo et al. 2019; Saucedo et al. 2019). Figure 15.1 indicates different natural polysaccharides, i.e. chitosan, carrageenan and sodium alginate, and their growth-regulating attributes besides their biological properties.

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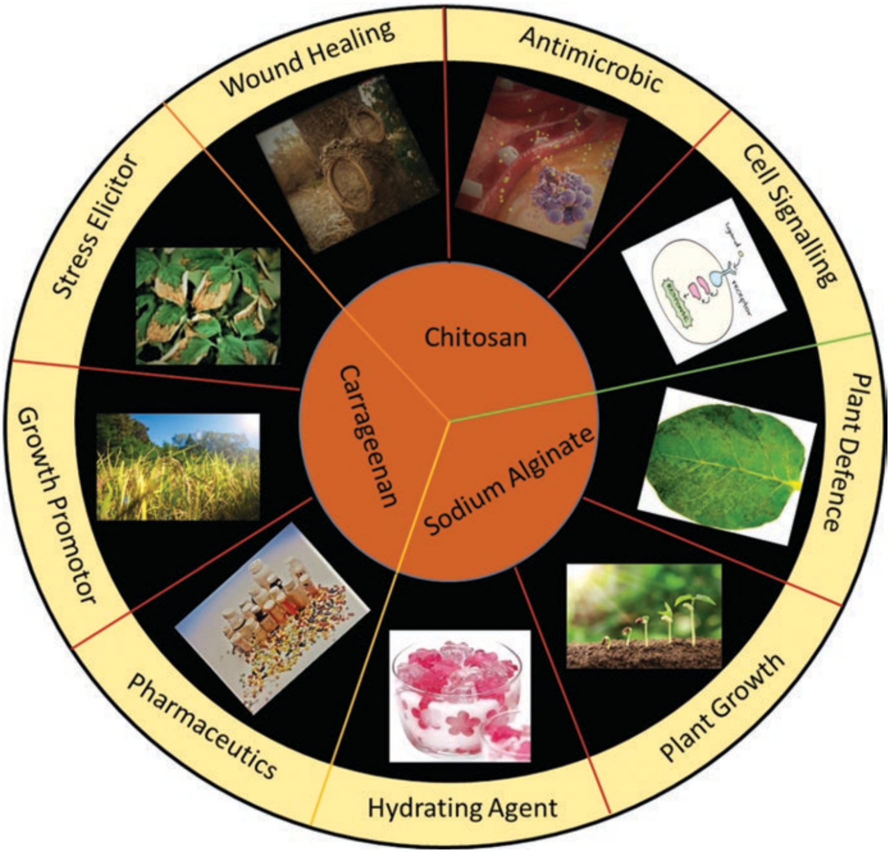

Fig. 15.1 Pictorial representation of the commercial applications of carrageenan, chitosan and sodium alginate along with their effect on plants

15.2 Chitosan

Chitin [(1,4)-2-acetamido-2-deoxy-β-D-glucan] is the second most abundant molecule in nature (Yan and Chen 2015) and is found primarily in crustacean shells, insects and fungi (Yan and Chen 2015; Jia et al. 2016; Turk 2019). Chitosan is a deacetylated chitin polymer that contains β-(1 → 4)-linked D-glucosamine and N-acetyl-D-glucosamine subunits (Malerba and Cerana 2016). Chitosan and its derivatives can further enrich chitosan properties due to their different physicochemical properties (size, density, surface area, etc.) enabling them to cross-talk with the cell wall and membrane more efficiently (Kim and Rajapakse 2005; Muley et al. 2019a). Multiples studies have reported that chitosan imparts a general trend of positive influence on plant growth and overall productivity (Pichyangkura and Chadchawan 2015; Malerba and Cerana 2016; Rabêlo et al. 2019). Figure 15.2

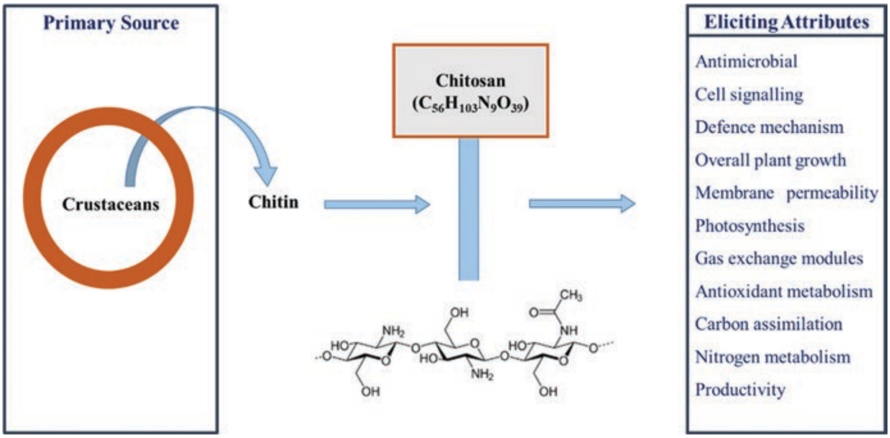

Fig. 15.2 Chitosan and its accompanied biological properties

traces the primary source of chitosan as well as induced responses in the biological systems.

15.2.1 Biological Activities of Chitosan

Chitosan has been reported to encompass a wide array of biological activities including antimicrobial, antitumor, antidiabetic, immunity-enhancing and wound-healing properties (Hayashi and Ito 2002; Xing et al. 2008; Zeng et al. 2008). Antimicrobial activities of chitosan chiefly comprise its antifungal and antibacterial properties (Xing et al. 2008; Meng et al. 2010). These properties, however, depend on multiple factors such as species of the microbe, concentration, deacetylation rate and molecular weight of chitosan or the pH of the solution itself (Xu et al. 2007; Xing et al. 2008; Yen et al. 2009). Chitosan can also constrain the formation of fungal spore, germ tube as well as mycelia (Meng et al. 2010). Various studies have suggested that chitosan can be used in food preservation and packaging industry given its antimicrobial potential (Chien and Chou 2006). Moreover, chitosan is cheaper, biocompatible, biodegradable and non-toxic and thus can be used in diverse fields including preservation and packaging of edible items (Chien and Chou 2006; García et al. 2015). Chitosan has been found effective against various economically important fungal strains including *Alternaria*, *Fusarium*, *Penicillium*, *Phytophthora* as well as *Botrytis* ((Meng et al. 2010) and the references therein). Therefore, chitosan can also be used as food preserver. Chitosan can keep food products away from fungal spoilage and thus elongate their shelf life (Liu et al. 2007), a decisive step in global food security itself.

Chitosan has been found effective against numerous bacteria as well (Du et al. 2009; Badawy et al. 2014). Chitosan solution has antipathogenic activity against the spread of many crop-threatening bacterial strains including *Xanthomonas* (Li et al. 2008). Keeping in view its action against fungi, it could be hypothesized that chitosan might inhibit bacterial biofilm formation and its further development by interacting with lipid bilayer and destabilizing bacterial membrane. As chitosan solution is generally prepared in acids given its low solubility in neutral or basic media, it can be argued that these properties might perhaps be more associated with acidic solvents. Thus, the extent of chitosan efficacy against such microbes is debatable. Recently, few chitosan derivatives with higher solubility in water were prepared and checked for various activities (Badawy and Rabea 2012; Tan et al. 2013; Badawy et al. 2014). It seemed more plausible that antimicrobial properties are to be more attributed to chitosan rather than the acidic solvent itself.

15.2.2 Role of Chitosan in Plant Growth Regulation

Chitosan has been reported as a growth promoter and signalling molecule in plants (Wang et al. 2015; Malerba and Cerana 2016; Muley et al. 2019b). Chitosan may also indulge in a complicated cascade of signal transduction that results in positive modulation of photosynthesis and multiple other related phenomena (Zhang et al. 2018). Chitosan being an important plant signalling molecule may target the nucleus and chloroplast (Pichyangkura and Chadchawan 2015; Rabêlo et al. 2019). Multiple genes associated with light reaction including those encoding for chlorophyll a/b binding protein and oxygen-evolving protein complex could be enhanced with chitosan application (Chamnanmanoontham et al. 2014). This might stabilize photosystem II and increased its efficiency and result in enhanced photosynthetic productivity. Similar regulatory effect was demonstrated in maize (Rabêlo et al. 2019), mint (Ahmad et al. 2019), potato (Muley et al. 2019b) and wheat (Zou et al. 2015).

Chlorophyllase is a crucial enzyme that catalyses the degradation of chlorophyll. Chitosan can suppress the expression level of the genes encoding for chlorophyllase resulting in increased photopigment content (Zhang et al. 2018). Chitosan is also capable of upregulating the translation of transcripts associated with photosynthesis as well as of those pertaining to the metabolism of carbon, nitrogen and amino acid (Zhang et al. 2018). Increased C- and N-assimilation plays a crucial role in source-sink potential and in the biosynthesis of growth- and yield-related molecules such as proteins and phenols (Chamnanmanoontham et al. 2014).

Plant mitochondria and chloroplasts produce different kinds of reactive oxygen species (ROS) and reactive nitrogen species (RNS) including peroxides and superoxides during various physiological processes under normal environment (Turk 2019). These compounds, collectively known as oxidants, have the tendency to damage lipid membrane via lipid peroxidation or alter membrane permeability via electrolyte leakage (Gupta et al. 2018; Zehra et al. 2020). Antioxidants are a group of compounds produced by plants as a counter-mechanism to regulate such phenomena. This cross-talk between oxidant and antioxidant signalling cascades contributes to ROS pathway and is directly linked with plant innate immunity (Rı et al. 2002; Gupta et al. 2018; Kohli et al. 2019).

Multiple studies (El-tantawy 2009; Chatelain et al. 2014; Wang et al. 2015; Ahmad et al. 2019; Muley et al. 2019b) have established that chitosan in different forms could enhance overall growth and yield in various crops. Chitosan also influences expression level of multiple glycolysis-related enzymes that might provide more energy to the plant (Chamnanmanoontham et al. 2014). However, chitosan might also exhibit some other different responses in different plants due to the fact that these responses chiefly depend on plant species and the concentration of chitosan used (Pongprayoon et al. 2013). As a general spectrum of chitosan effect on various plant phenomena, it has been reported to improve the biosynthesis of photosynthetic pigments, i.e. chlorophyll and carotenoids (Ahmad et al. 2017). Similar eliciting effects are also exhibited by source-sink potential through providing more efficient mineral uptake and their assimilation (Ahmad et al. 2017). Chitosan also plays a decisive role in plants during adverse environmental conditions. It upregulates antioxidant metabolism and ROS pathway and assists in enhanced production for various enzymatic as well as non-enzymatic antioxidants to resist the cellular damage (Chandra et al. 2015). These regulations, ultimately, help the plant to exhibit enhanced growth and overall production and also to survive in a stressful environment (Muley et al. 2019b; Rabêlo et al. 2019). Table 15.1 emphasizes on particular

Table 15.1 Eliciting effects of chitosan and its derivatives on various plant species

Plant	Eliciting effects on	Reference
Tomato	Plant height, fresh and dry weight, number of branches and leaves and marketable yield	El-tantawy (2009)
Coffee	Photosynthetic pigments, mineral nutrients (N, P, K, Ca and mg), overall growth and productivity	N. A. Dzung et al. (2011)
Maize	Root and shoot growth, antioxidant metabolism, leaf number, ear length and grain yield	Choudhary et al. (2017)
Chilli	Shoot biomass, chlorophyll content, fruit number and fruit weight	P. D. Dzung et al. (2017)
Common bean	Plant height, number of leaves and branches, leaf area, fresh and dry biomass, content of mineral nutrient (N, P, K), total carbohydrate and protein and productivity	Abu-Muriefah (2013)
Mint	Plant biomass, chlorophyll and carotenoid contents, activities of CA and NR enzymes, mineral nutrient (N, P and K) status and oil yield	Ahmad et al. (2017)
Rice	Expression level of genes pertaining to various physiological phenomena, overall plant growth and productivity	Chamnanmanoontham et al. (2014)
Tea	Antioxidant metabolism and plant immunity	Chandra et al. (2015)
Soybean	Photosynthetic modules, e.g. net photosynthetic rate and stomatal conductance	W. M. Khan et al. (2002)
Wheat	Overall plant growth, antioxidant capacity, sucrose and starch content and regulation of miRNA and mRNA expression profiles	Zhang et al. (2018)

phenomena that were associated with application of chitosan and its derivatives in different plants of economic importance.

15.3 Carrageenan

Carrageenan is generic name for the water-soluble and sulphated linear polysaccharides mainly found in the cell walls of various red algae (Mercier et al. 2001). It is composed of D-galactose and 3,6-anydrogalactose units joined through α-1,3 and β-1,4-glycosidic linkage (Di Rosa 1972; Necas and Bartosikova 2013). Carrageenan can however vary based on the number and position of the sulphate groups and the content of 3,6-anhydrogalactose units (Hashmi et al. 2012; Necas and Bartosikova 2013). Kappa (one sulphate group), iota (two sulphate groups) and lambda (three sulphate groups) are three such commercially utilized carrageenan variants (De Ruiter and Rudolph 1997). Higher sulphate ester levels confer lower solubility temperature and thus weaker gel strength (Necas and Bartosikova 2013). These sulphate groups make carrageenan chemically active, giving it various biological properties. Figure 15.3 unfolds carrageenan from its primary source along with its interaction with multiple plant phenomena.

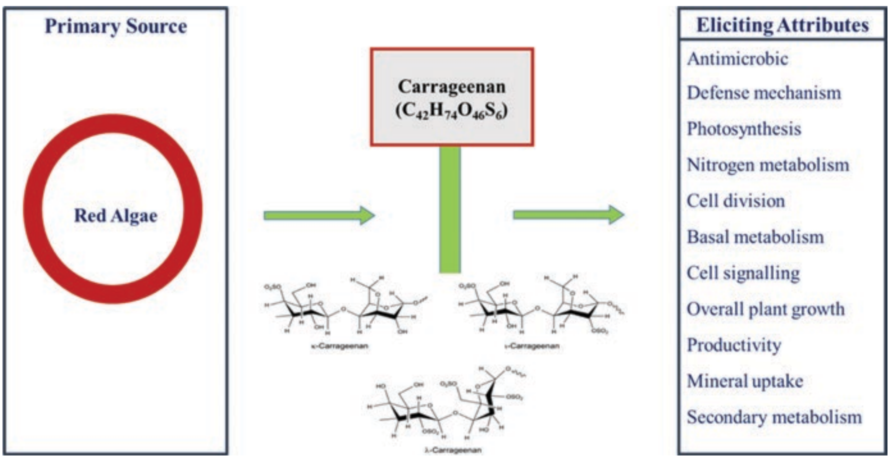

Fig. 15.3 Carrageenan and its accompanied biological properties

15.3.1 Biological Activities of Carrageenan

Carrageenans (CGs) consist of numerous biological properties including induction of experimental inflammation and inflammatory pain. Aside from these functions, they found to have several potential pharmaceutical formulations including antitumour, antihyperlipidemic, immunomodulatory and anticoagulant activities (Morris 2003; Zhou et al. 2004; Campo et al. 2009). Recent researches have demonstrated that carrageenan is an extraordinarily potent infection inhibitor of a wide range of genital human papillomaviruses (HPVs), and it is also indicated that HPV transmission may be cured by carrageenan-based sexual lubricant gels (Buck et al. 2006). However, questions about the safety of CG uses as food additive and pharmaceutical adjuvant have been raised. Besides, its long-term safety is a major concern as CG is used as an inducer of inflammatory responses in laboratory animals for the investigation of anti-inflammatory drugs (Li et al. 2014).

Several research studies also mentioned the anti-HIV properties of CG, but their usual mode of action in anticoagulant is considered to be an adverse reaction when used as a therapeutic drug for AIDS (Necas and Bartosikova 2013). Although all kinds of CGs possess antioxidant activity, λ carrageenan exhibited the highest antioxidant and free radical scavenging activity. A positive correlation has been observed between sulphate content and antioxidant activity (Rocha De Souza et al. 2007). A few CGs are found to affect strong macrophage activation, while some restrict macrophage functions. An experiment conducted on Fischer 344 rats, feeding on foods containing 15% kappa/lambda CGs from *Gahnia radula*, showed a cholesterol-reducing effect (Zia et al. 2017).

15.3.2 Role of Carrageenan in Plant Growth Regulation

To achieve crop protection, by activating or eliciting their natural defence system to introduce desired resistance, is the most effective way and an environmentally safer approach to the problem. The strong elicitors narrated in literature are diverse in nature including oligosaccharides, polysaccharides, peptides, proteins and lipids, and it has been confirmed that polysaccharides purified from seaweeds as well as derived oligosaccharides play a significant role in plant defence responses (Bi et al. 2011). Carrageenans are considered to play a significant role in plant signalling and defence under several adverse environmental conditions (Mercier et al. 2001). Several experiments have been conducted to scrutinize the elicitor activity of carrageenans. *Hypnea musciformis*, a rich source to obtain kappa carrageenan, has been evaluated as an elicitor or inducer of plant defence responses in terms of phytoalexin synthesis and induced browning and resulted as a potent plant protector as well as growth-promoting agent in plants (Arman and Qader 2012). Carrageenans and their oligomeric form, the oligocarrageenans (OCs), modulate the activity of different plant defence pathways, including jasmonate, salicylate and ethylene signalling pathways which in turn induce plant defence responses against viruses, viroids, bacteria, fungi and insects (Shukla et al. 2016).

Various endogenous and environmental factors such as light, hormones, temperature and nutrient availability affect plant growth and development. Moreover, it has been observed that marine algae oligosaccharides stimulate plant growth. Various treatments of oligocarrageenans K, L and I exhibited increased growth of commercial tobacco plants by enhancing photosynthesis, basal metabolism, nitrogen assimilation and cell division, as well as that of other plants of commercial interest, and enhanced protection against tobacco mosaic virus (TMV) infection in tobacco plants (Castro et al. 2012). In addition, accumulation of several phenylpropanoid compounds (PPCs) with microbial activity increased by oligocarrageenans improves protection against viral, fungal and bacterial infections in tobacco plants. Moreover, OCs induce the level of essential oil and increase cellulose content and some PPCs with antimicrobial activities, indicating that defence against pathogen may also be cured (González et al. 2013). A red macroalga, *Kappaphycus alvarezii*, has a great economic importance due to its production of kappa carrageenan. It produces and accumulates photoprotective compounds such as carotenoids and mycosporin-like amino acids (MAAs), which absorb UVR energy directly or indirectly (Schmidt et al. 2010).

Liquid extracts of seaweeds have been reported to enhance the growth of plants, increase yield and quality, improve resistance to disease and pest, increase mineral uptake from soil and antioxidant properties and amend resistance to abiotic stresses (salinity, drought, heavy metal stress and extreme temperatures). Carrageenans are the best characterized seaweed elicitors that have the potential to activate disease resistance in plants and animals (Mousavi et al. 2018). OC kappa enhances C-, N- and S-assimilation and improves growth-promoting hormone content and growth in pine trees; therefore, it may account for useful biotechnological tool to increase growth in pine forests (Saucedo et al. 2015). Several research experiments have been conducted and analysed the effects of carrageenan on growth and secondary metabolite status in plants. Several physiological and biological activities such as plant growth, physiological attributes, herbage yield and content and yield of alkaloids (vincristine, vinblastine) of periwinkle and the content and yield of essential oil in mint improved after foliar application of the degraded marine polysaccharides (Naeem et al. 2012a, 2015a).

It is well studied that growth and development in plants, algae, mammals and nematodes is controlled by the kinase target of rapamycin (TOR). It is a key regulatory kinase of the TOR pathway and is a phosphoinositol-related kinase (PIK) having protein serine/threonine protein kinase activity. In *E. globulus* trees, the stimulation of growth induced by OC kappa, by the activation of TOR pathway and increased expression of genes encoding protein involved in photosynthesis and enzymes of basal metabolism, has been reported (Saucedo et al. 2019). Table 15.2 weights on the eliciting effects of carrageenan and its derivatives on growth and physiology of various crops.

Table 15.2 Eliciting effects of carrageenan and its derivatives on various plant species

Plant	Eliciting effects on	Reference
Mung bean	Disease resistance and marketable yield	Gatan et al. (2019)
Fennel	Shoot length, plant biomass, photosynthetic pigments, activities of CA and NR enzymes, contents of N and P, overall productivity	Hashmi et al. (2012)
Maize	Plant length; number of pods, branches and leaves; and secondary metabolism	Bi et al. (2011)
Pine	Assimilation of carbon, nitrogen and Sulphur, contents of auxin and gibberellin and basal metabolism	Saucedo et al. (2015)
Peanut	Seed germination, flowering, plant height, pod length and number, seed weight and total yield	Abad et al. (2018)
Tobacco	Photosynthesis, basal metabolism and overall productivity	Castro et al. (2012)
Basil	Shoot length, leaf area, phenolic and antioxidant content and defence system	Mousavi et al. (2018)
Tasmanian blue gum	Plant height, photosynthesis, levels of sugar and trehalose, expression of transcripts pertaining to glucose, basal and secondary metabolism	Saucedo et al. (2019)
Lemongrass	Photosynthetic pigment, osmotic and turgor potential, antioxidant metabolism, overall growth and oil yield	Singh et al. (2017)
Chickpea	Defence system and overall growth promotion	Arman and Qader (2012)

15.4 Sodium Alginate

Alginates are natural polysaccharides chiefly derived from marine brown algae (Phaeophyceae) (Mollah et al. 2009; Khan et al. 2011). Commercial varieties of alginate are extracted from seaweed, including giant kelp *Macrocystis pyrifera*, *Ascophyllum nodosum*, *Ecklonia maxima*, *Sargassum sinicola* and various types of *Laminaria* (Hernández-Carmona et al. 2013). Sodium alginate ($NaC_6H_7O_6$) is the sodium salt of alginic acid and is composed of poly-β-(1, 4) D-mannuronic acid and poly-α-(1, 4) L-guluronic acid (Xu et al. 2006; El-Mohdy 2017). It ranges from white to yellowish brown and have filamentous, granular and powdered forms and is widely used in pharmaceutical, biotechnological and food sectors (Mollah et al. 2009; Khan et al. 2011). Annexed Fig. 15.4 represents sodium alginate and its chief source. Consecutive effects of sodium alginate and its derivatives on various plants and microbes are also illustrated in the same figure.

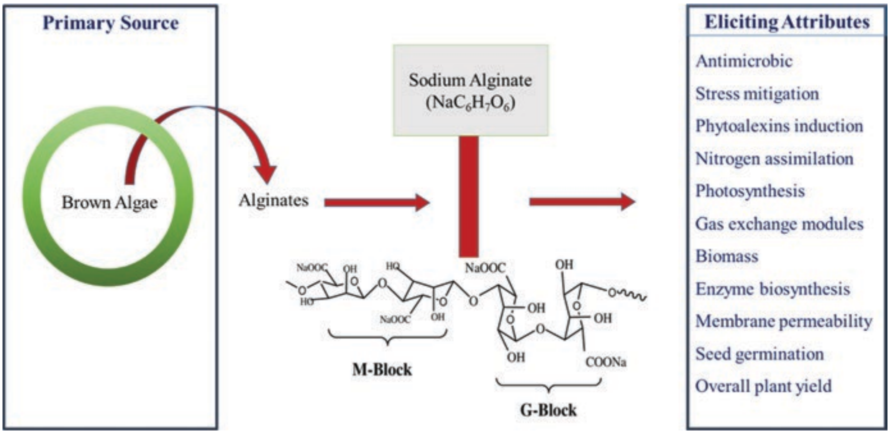

Fig. 15.4 Sodium alginate and its accompanied biological properties

15.4.1 Biological Activities of Sodium Alginate

Sodium alginate plays a major role in the structural component of the cell wall and intercellular matrix in organisms from Phaeophyceae and *Laminaria* (Hernández-Carmona et al. 2013). This marine polysaccharide consists of residues of mannuronic acid (M-block) and guluronic acid (G-block) (El-Mohdy 2017). Monomers are arranged in three types of block structure. These blocks may be homopolymeric block (M-block, G-block) or heteropolymeric block (MG-block). MG-block is known for its most flexible chain formation while M-block for its strong immunostimulating property (Pegg 2012). The fraction of mannuronic acid (M-block) and guluronic acid (G-block) of sodium alginate showed antibacterial activity against *Escherichia coli*, *Staphylococcus aureus* and *Bacillus subtilis* (Hu et al. 2005).

Marine polysaccharides are highly reactive and peculiar compounds with thermo-reversible gel formation ability and have widespread use in pharmaceutical industry and bioengineering products (Hien et al. 2000; Aftab et al. 2014). Alginates are also exploited in drug delivery and as hydrogels for immobilizing cells and enzymes due to their mild conditions of cross-linking through bivalent cations (Ca^{2+}) (Russo et al. 2007; Liu and Li 2016). These characteristics can also be further altered by chemical modification, blending and integrating biodegradable additives which allows to tailor the final properties of the polysaccharides and opens the doors to wider applications, particularly in pharmaceutical area (Gomez d'Ayala et al. 2007).

Commercially, sodium alginates are also exploited in gel formation given their efficient and rapid water-absorbing property, sometimes absorbing multiple times of its own weight in water (Jamaludin et al. 2017). Moreover, carbohydrates like sodium alginate, chitosan, carrageenan, cellulose and pectin help in recycling bio-resources and reducing environmental pollution. These carbohydrates in various forms can induce different kinds of biological activities including antimicrobial activity and phytoalexin induction (Kume et al. 2002).

15.4.2 Role of Sodium Alginate in Plant Growth Regulation

Sodium alginate in various forms and concentrations can impart a general trend of improved overall vegetative growth in different crops. SA has the potential to enhance plant height, biomass (both fresh and dry weight), number of tillers and leaves as well as leaf area (Hien et al. 2000; Iwasaki and Matsubara 2000; Kume et al. 2002; Hu et al. 2004; Hegazy et al. 2009; Mollah et al. 2009; Qureshi 2010; Sarfaraz et al. 2011; Naeem et al. 2015b). In addition to overall growth, sodium alginate renders stimulating effects on seed germination as well (Jamsheer 2010; Khan et al. 2011). The effect of alginate-derived oligosaccharide concentration on α- and β-amylase activities in different germination stages of maize seeds enhanced the seed germination by increasing the activities of several enzymes beneficial for germination (Hu et al. 2004). These SA-induced effects could also be attributed to the sodium alginate's interaction with plant cell signalling and its perceived regulation of gene expression (Khan et al. 2011).

These SA-induced responses can be understood by the fact that application of SA can induce multiple physiological and biochemical changes in plants. On a molecular level, SA is capable of regulating the biosynthesis of various enzymes (Ma et al. 2010; Khan et al. 2011) and the references therein) including those pertaining to nitrogen and carbon metabolism. Nitrate reductase (NR) is a key enzyme in nitrogen metabolism that assists in the first step of nitrogen assimilation in plant system through conversion of nitrate into nitrite. Thus, an efficient NR enzyme provides enough raw materials for the synthesis of various structural and functional biomolecules including amino acids and lipids. Various studies reported the direct influence of SA on the NR activity where it was found that SA can significantly ($p \leq 0.05$) upregulate the activity of NR enzyme in various crops of economic importance, e.g. fennel (Sarfaraz et al. 2011), lemongrass (Idrees et al. 2012) and mint (Naeem et al. 2012b). As a result, SA assist in maintaining a higher nitrogen content that ultimately influences the content of photosynthetic pigments (i.e. chlorophyll and carotenoid) through amino acid, protein and lipid biosynthesis (Idrees et al. 2012). Another key enzyme in carbon metabolism is carbonic anhydrase (CA). SA has also been reported to upregulate the CA activity in different crops (Luan et al. 2003; Khan et al. 2011; Naeem et al. 2015b).

Another aspect of SA-induced physiological response can be observed on plant gas exchange modules. Net photosynthetic rate (P_N) and stomatal conductance (g_s) can play a decisive role in determining overall plant growth and productivity. SA positively influence both P_N (Luan et al. 2003) and g_s (Naeem et al. 2015b) possibly because of the SA-induced photosynthetic pigment content (Mollah et al. 2009; Sarfaraz et al. 2011) and enhanced membrane permeability (Khan and Srivastava 1998). Due to its regulating effects on membrane permeability as well as on protoplast formation, alginate and its derivatives have also been labelled as endogenous elicitors (Akimoto et al. 1999). Similar regulating effects of SA on secondary metabolism were noted otherwise where the content of secondary metabolites exhibited positive correlation with sodium alginate application (Idrees et al. 2011; Khan et al. 2011; Naeem et al. 2015b).

Some other miscellaneous SA-induced effects on plant system includes enhanced water-use efficiency (Idrees et al. 2011); phosphoenolpyruvate (PEP) carboxylase activity and protein content (Idrees et al. 2012); content of nitrogen, phosphorus and potassium (leaf NPK); and phytoalexin induction (Mollah et al. 2009; Khan et al. 2011; Sarfaraz et al. 2011; Idrees et al. 2012). Sodium alginate has also been attributed to provide resistance against various disease and adverse environmental conditions, thus contributing in plant defence system by ameliorating antioxidant metabolism and reactive oxygen species pathway (Hien et al. 2000; Liu et al. 2009; Ali et al. 2014). The combination of *Alteromonas macleodii* (common marine bacterium), as exogenous elicitor, and alginate oligomers, acting as both endogenous elicitor and scavenger of active oxygen species, reportedly minimized the cell growth inhibition and enhanced 5′-phosphodiesterase production in periwinkle (Aoyagi et al. 2006).

Various researches have demonstrated that SA is significantly potent in imparting an eliciting effect on the overall productivity and plant yield. SA can enhance the weights of seed and capsule in opium (Khan et al. 2011), oil production in lemongrass (Idrees et al. 2012) and herbage yield in periwinkle (Naeem et al. 2015b) along with the productivity of barley, carrot, cabbage, maize, peanut rice, tea and tomato (Hien et al. 2000; Hu et al. 2004; Hegazy et al. 2009; Liu et al. 2009). Table 15.3 represents plant growth, productivity and immunity promotion in different crops by sodium alginate and its derivatives.

Similar to chitosan and carrageenan, sodium alginate is also an efficient plant growth regulator which not only hampers yield loss during adverse environment but also promotes overall plant growth and productivity. Although the exact mechanism for these effects is not yet fully known, in the light of current advancements, we can assume that these NPs interact extensively with various vital physiological processes which play a decisive role in determining the fate of overall plant growth and productivity (Chamnanmanoontham et al. 2014). A general idea for this mechanism can be understood by annexed Fig. 15.5., where a hypothetical model for oligomeric action of chitosan, carrageenan and sodium alginate in plants is portrayed.

15.5 Conclusion and Future Prospective

Marine polysaccharides (chitosan, carrageenan and sodium alginate) in various forms seem to enhance overall plant growth and productivity. It is now known that these marine polysaccharides can act as a signalling molecule which interact with plant physiology in a complex cascade mechanism and produce these favourable effects (Mercier et al. 2001; Khan et al. 2011; Shukla et al. 2016). While all the three

Table 15.3 Eliciting effects of sodium alginate and its derivatives on various plant species

Plant	Eliciting effects on	Reference
Maize	Seed germination, α- and β-amylase activity, overall growth and productivity	Hegazy et al. (2009), Hu et al. (2004)
Peanut	Shoot growth, plant biomass and defence mechanism	Hien et al. (2000)
Mint	Shoot growth, biomass and essential oil yield	Naeem et al. (2012b)
Periwinkle	Plant height, leaf area index, fresh weight and dry weight, increased enzyme activities and photosynthetic rate	Luan et al. (2003)
Red amaranth	Shoot growth, leaf number, leaf area, dry weight, chlorophyll and carotenoid contents and phytoalexin induction	Mollah et al. (2009)
Opium poppy	Plant length; dry weight; chlorophyll and carotenoid contents; activities of CA and NR enzymes; cell signalling; weights of seeds, capsule and crude opium; and alkaloid content	Khan et al. (2011)
Fennel	Contents of chlorophyll and carotenoid, efficiency of carbon and nitrogen assimilatory enzymes, leaf NPK content, plant height, leaf size, biomass and overall plant productivity	Sarfaraz et al. (2011)
Lemon-scented eucalyptus	Plant growth, fresh and dry weight, leaf number and size, photosynthetic pigments, leaf NPK and essential oil production	Ali et al. (2014)
Faba bean	Biomass, germination, plant height, leaf width and seed yield	El-Mohdy (2017)
Lemongrass	Shoot growth; leaf and tiller number; dry weight; photosynthetic pigments; leaf NPK content; activities of CA, NR and PEP carboxylase; protein content; and essential oil yield	Idrees et al. (2012)

reviewed polysaccharides, i.e. chitosan, carrageenan and sodium alginate, have a general positive influence on plant overall growth and productivity, they possess few attributes that make a distinction among them. While chitosan can be used in preservation and safety of food and dairy products, sodium alginate can be exploited as a gelling or hydrating agent (Piculell 1995; Chien and Chou 2006; Liu et al. 2007). Similarly, carrageenan can be extensively used in pharmaceutical and drug development industries.

Although this review assessed the role of chitosan, carrageenan and sodium alginate on plant biology, there are few questions still left to be answered. Further investigations could reveal important insights about the exact mechanism responsible for such NP-induced responses in various crops. Additionally, critical evaluation of such responses through transcriptomics, epigenetics, radiation biology and bioinformatics might give us a better understanding of the cross-talk of NPs with other signalling pathways in various crops.

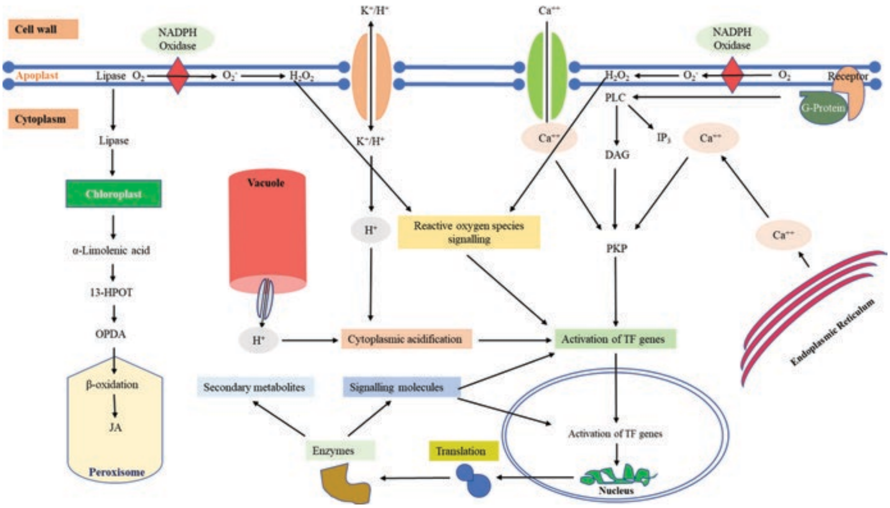

Fig. 15.5 Hypothetical model for the mechanism of carrageenan, chitosan and sodium alginate in oligomeric form. (13-HPOT, 13-hydroperoxy-linolenic acid; OPDA, 12-oxophytodienoic acid; DAG, diacylglycerol; IP_3, inositol triphosphate; JA, methyl jasmonate; PKP, protein kinase phosphatase; PLC, phospholipase C; TF, transcription factors)

References

Abad LV, Aurigue FB, Montefalcon DRV, Manguiat PH, Carandang FF, Mabborang SA, Hizon MGS, Abella MES (2018) Effect of radiation-modified kappa-carrageenan as plant growth promoter on peanut (Arachis hypogaea L.). Radiat Phys Chem 153:239–244. https://doi.org/10.1016/j.radphyschem.2018.10.005

Abu-Muriefah SS (2013) Effect of chitosan on common bean (Phaseolus vulgaris L.) plants grown under water stress conditions. Int Res J Agri Sci Soil Sci 3(6):2251–2244

Aftab T, Khan MMA, Naeem M, Idrees M, Siddiqi TO, Moinuddin, & Varshney, L. (2014) Effect of irradiated sodium alginate and phosphorus on biomass and artemisinin production in Artemisia annua. Carbohydr Polym 110:396–404. https://doi.org/10.1016/j.carbpol.2014.04.045

Ahmad B, Khan MMA, Jaleel H, Sadiq Y, Shabbir A, Uddin M (2017) Exogenously sourced γ-irradiated chitosan-mediated regulation of growth, physiology, quality attributes, and yield in mentha piperita L. Turk J Biol 41(2):388–401. https://doi.org/10.3906/biy-1608-64

Ahmad B, Jaleel H, Shabbir A, Khan MMA, Sadiq Y (2019) Concomitant application of depolymerized chitosan and GA3 modulates photosynthesis, essential oil and menthol production in peppermint (Mentha piperita L.). Sci Hortic 246(November 2018):371–379. https://doi.org/10.1016/j.scienta.2018.10.031

Akimoto C, Aoyagi H, Tanaka H (1999) Endogenous elicitor-like effects of alginate on physiological activities of plant cells. Appl Microbiol Biotechnol 52(3):429–436. https://doi.org/10.1007/s002530051542

Ali A, Khan MMA, Uddin M, Naeem M, Idrees M, Hashmi N, Dar TA, Varshney L (2014) Radiolytically depolymerized sodium alginate improves physiological activities, yield attributes and composition of essential oil of Eucalyptus citriodora Hook. Carbohydr Polym 112:134–144. https://doi.org/10.1016/j.carbpol.2014.05.070

Aoyagi H, Akimoto-Tomiyama C, Tanaka H (2006) Preparation of mixed alginate elicitors with high activity for the efficient production of 5′-phosphodiesterase by Catharanthus roseus cells. Biotechnol Lett 28(19):1567–1571. https://doi.org/10.1007/s10529-006-9124-5

Arman M, Qader SAU (2012) Structural analysis of kappa-carrageenan isolated from Hypnea musciformis (red algae) and evaluation as an elicitor of plant defense mechanism. Carbohydr Polym 88(4):1264–1271. https://doi.org/10.1016/j.carbpol.2012.02.003

Badawy MEI, Rabea EI (2012) Characterization and antimicrobial activity of water-soluble N-(4-carboxybutyroyl) chitosans against some plant pathogenic bacteria and fungi. Carbohydr Polym 87(1):250–256. https://doi.org/10.1016/j.carbpol.2011.07.054

Badawy MEI, Rabea EI, Taktak NEM (2014) Antimicrobial and inhibitory enzyme activity of N-(benzyl) and quaternary N-(benzyl) chitosan derivatives on plant pathogens. Carbohydr Polym 111:670–682. https://doi.org/10.1016/j.carbpol.2014.04.098

Bi F, Iqbal S, Arman M, Ali A, Hassan, M. ul. (2011) Carrageenan as an elicitor of induced secondary metabolites and its effects on various growth characters of chickpea and maize plants. J Saudi Chem Soc 15(3):269–273. https://doi.org/10.1016/j.jscs.2010.10.003

Buck CB, Thompson CD, Roberts JN, Müller M, Lowy DR, Schiller JT (2006) Carrageenan is a potent inhibitor of papillomavirus infection. PLoS Pathog 2(7):0671–0680. https://doi.org/10.1371/journal.ppat.0020069

Campo VL, Kawano DF, da Silva DB, Carvalho I (2009) Carrageenans: biological properties, chemical modifications and structural analysis – a review. Carbohydr Polym 77(2):167–180. https://doi.org/10.1016/j.carbpol.2009.01.020

Castro J, Vera J, González A, Moenne A (2012) Oligo-carrageenans stimulate growth by enhancing photosynthesis, basal metabolism, and cell cycle in tobacco plants (var. burley). J Plant Growth Regul 31(2):173–185. https://doi.org/10.1007/s00344-011-9229-5

Chamnanmanoontham N, Pongprayoon W, Pichayangkura R, Roytrakul S, Chadchawan S (2014) Chitosan enhances rice seedling growth via gene expression network between nucleus and chloroplast. Plant Growth Regul 75(1):101–114. https://doi.org/10.1007/s10725-014-9935-7

Chandra S, Chakraborty N, Dasgupta A, Sarkar J, Panda K, Acharya K (2015) Chitosan nanoparticles: a positive modulator of innate immune responses in plants. Sci Rep 5:1–14. https://doi.org/10.1038/srep15195

Chatelain PG, Pintado ME, Vasconcelos MW (2014) Evaluation of chitooligosaccharide application on mineral accumulation and plant growth in Phaseolus vulgaris. Plant Sci 215–216:134–140. https://doi.org/10.1016/j.plantsci.2013.11.009

Chien PJ, Chou CC (2006) Antifungal activity of chitosan and its application to control post-harvest quality and fungal rotting of tankan citrus fruit (Citrus tankan Hayata). J Sci Food Agric 86(12):1964–1969. https://doi.org/10.1002/jsfa.2570

Choudhary RC, Kumaraswamy RV, Kumari S, Sharma SS, Pal A, Raliya R, Biswas P, Saharan V (2017) Cu-chitosan nanoparticle boost defense responses and plant growth in maize (Zea mays L.). Sci Rep 7(1):1–11. https://doi.org/10.1038/s41598-017-08571-0

De Ruiter GA, Rudolph B (1997) Carrageenan biotechnology. Trends Food Sci Technol 8(12):389–395. https://doi.org/10.1016/S0924-2244(97)01091-1

Di Rosa M (1972) Biological properties of carrageenan. J Pharm Pharmacol 24(2):89–102. https://doi.org/10.1111/j.2042-7158.1972.tb08940.x

Du WL, Niu SS, Xu YL, Xu ZR, Fan CL (2009) Antibacterial activity of chitosan tripolyphosphate nanoparticles loaded with various metal ions. Carbohydr Polym 75(3):385–389. https://doi.org/10.1016/j.carbpol.2008.07.039

Dzung NA, Khanh VTP, Dzung TT (2011) Research on impact of chitosan oligomers on biophysical characteristics, growth, development and drought resistance of coffee. Carbohydr Polym 84(2):751–755. https://doi.org/10.1016/j.carbpol.2010.07.066

Dzung PD, Van Phu D, Du BD, Ngoc LS, Duy NN, Hiet HD, Nghia DH, Thang NT, Van Le B, Hien NQ (2017) Effect of foliar application of oligochitosan with different molecular weight on growth promotion and fruit yield enhancement of chili plant. Plant Prod Sci 20(4):389–395. https://doi.org/10.1080/1343943X.2017.1399803

El-Mohdy HLA (2017) Radiation-induced degradation of sodium alginate and its plant growth promotion effect. Arab J Chem 10:S431–S438. https://doi.org/10.1016/j.arabjc.2012.10.003

El-tantawy EM (2009) Behavior of tomato plants as affected by spraying with chitosan and aminofort as natural stimulator substances under application of soil organic amendments. Pak J Biol Sci 12(17):1164

FAO (2015) AQUASTAT Country Profile – India. http://www.fao.org/aquastat/en/countries-and-basins/country-profiles/country/IND

García MA, de la Paz N, Castro C, Rodríguez JL, Rapado M, Zuluaga R, Gañán P, Casariego A (2015) Effect of molecular weight reduction by gamma irradiation on the antioxidant capacity of chitosan from lobster shells. J Radiat Res Appl Sci 8(2):190–200. https://doi.org/10.1016/j.jrras.2015.01.003

Gatan, MGB, Montefalcon, DRV, Aurigue, FB, Abad, LV (2019) Effect of radiation-modified kappa-carrageenan on the morpho-agronomic characteristics of mungbean [Vigna radiata (L.) R. Wilczek]. Philipp J Sci 149(S1):135–143

Gomez d'Ayala G, De Rosa A, Laurienzo P, Malinconico M (2007) Development of a new calcium sulphate-based composite using alginate and chemically modified chitosan for bone regeneration. J Biomed Mater Res A 81(4):811–820

González A, Castro J, Vera J, Moenne A (2013) Seaweed oligosaccharides stimulate plant growth by enhancing carbon and nitrogen assimilation, basal metabolism, and cell division. J Plant Growth Regul 32(2):443–448. https://doi.org/10.1007/s00344-012-9309-1

Gupta DK, Palma JM, Corpas FJ (2018) Antioxidants and antioxidant enzymes. Free Radic Biol Med 100:S92–S93. https://doi.org/10.1016/j.freeradbiomed.2016.10.230

Hashmi N, Khan MM, Moinuddin A, Idrees M, Khan ZH, Ali A, Varshney L (2012) Depolymerized carrageenan ameliorates growth, physiological attributes, essential oil yield and active constituents of Foeniculum vulgare mill. Carbohydr Polym 90(1):407–412. https://doi.org/10.1016/j.carbpol.2012.05.058

Hayashi K, Ito M (2002) Antidiabetic action of low molecular weight chitosan in genetically obese diabetic KK-ay mice. Biol Pharm Bull 25(2):188–192. https://doi.org/10.1248/bpb.25.188

Hegazy EA, Abdel-Rehim H, Diaa DA, El-Barbary A (2009) Report: Controlling of degradation effects in radiation processing of polymers. In Controlling of Degradation Effects in Radiation Processing of Polymers; IAEA: Vienna, Austria, pp. 67–84

Hernández-Carmona G, Freile-Pelegrín Y, Hernández-Garibay E (2013) Conventional and alternative technologies for the extraction of algal polysaccharides. In: Functional Ingredients from Algae for Foods and Nutraceuticals. https://doi.org/10.1533/9780857098689.3.475

Hien NQ, Nagasawa N, Tham LX, Yoshii F, Dang VH, Mitomo H, Makuuchi K, Kume T (2000) Growth-promotion of plants with depolymerized alginates by irradiation. Radiat Phys Chem 59(1):97–101. https://doi.org/10.1016/S0969-806X(99)00522-8

Hu X, Jiang X, Hwang H, Liu S, Guan H (2004) Promotive effects of alginate-derived oligosaccharide on maize seed germination. J Appl Phycol 16(1):73–76. https://doi.org/10.1023/B:JAPH.0000019139.35046.0c

Hu X, Jiang X, Gong J, Hwang H, Liu Y, Guan H (2005) Antibacterial activity of lyase-depolymerized products of alginate. J Appl Phycol 17(1):57–60. https://doi.org/10.1007/s10811-005-5524-5

Idrees M, Naeem M, Alam M, Aftab T, Hashmi N, Khan MMA, Moinuddin, & Varshney, L. (2011) Utilizing the γ-irradiated sodium alginate as a plant growth promoter for enhancing the growth, physiological activities, and alkaloids production in Catharanthus roseus L. Agric Sci China 10(8):1213–1221. https://doi.org/10.1016/S1671-2927(11)60112-0

Idrees M, Nasir S, Naeem M, Aftab T, Khan MMA, Moinuddin, & Varshney, L. (2012) Gamma irradiated sodium alginate induced modulation of phosphoenolpyruvate carboxylase and production of essential oil and citral content of lemongrass. Ind Crop Prod 40(1):62–68. https://doi.org/10.1016/j.indcrop.2012.02.024

Iwasaki KI, Matsubara Y (2000) Purification of alginate oligosaccharides with root growth-promoting activity toward lettuce. Biosci Biotechnol Biochem 64(5):1067–1070. https://doi.org/10.1271/bbb.64.1067

Jamaludin J, Adam F, Rasid RA, Hassan Z (2017) Thermal studies on Arabic gum-carrageenan polysaccharides film. Chem Eng Res Bull, 19, 80–86. https://doi.org/10.3329/cerb.v19i0.33800

Jamsheer MK (2010). Response of beetroot (Beta vulgaris L.) to the application of phosphorus and gamma-irradiated sodium alginate. Doctoral dissertation, M. Sc. Thesis. Aligarh Muslim University, Aligarh

Jia X, Meng Q, Zeng H, Wang W, Yin H (2016) Chitosan oligosaccharide induces resistance to tobacco mosaic virus in Arabidopsis via the salicylic acid-mediated signalling pathway. Sci Rep 6(November 2015):1–12. https://doi.org/10.1038/srep26144

Khan MG, Srivastava HS (1998) Changes in growth and nitrogen assimilation in maize plants induced by NaCl and growth regulators. Biol Plant 1(41):93–99. https://doi.org/10.1023/A:1001768601359

Khan WM, Prithiviraj B, Smith DL (2002) Effect of foliar application of chitin and chitosan oligosaccharides on photosynthesis of maize and soybean. Photosynthetica 40(4):621–624

Khan ZH, Khan MMA, Aftab T, Idrees M, Naeem M (2011) Influence of alginate oligosaccharides on growth, yield and alkaloid production of opium poppy (Papaver somniferum L.). Front Agric China 5(1):122–127. https://doi.org/10.1007/s11703-010-1056-0

Kim SK, Rajapakse N (2005) Enzymatic production and biological activities of chitosan oligosaccharides (COS): a review. Carbohydr Polym 62(4):357–368. https://doi.org/10.1016/j.carbpol.2005.08.012

Kohli SK, Khanna K, Bhardwaj R, Abd Allah EF, Ahmad P, Corpas FJ (2019) Assessment of subcellular ROS and NO metabolism in higher plants: multifunctional signaling molecules. Antioxidants 8(12). https://doi.org/10.3390/antiox8120641

Kume T, Nagasawa N, Yoshii F (2002) Utilization of carbohydrates by radiation processing. Radiat Phys Chem 63(3–6):625–627. https://doi.org/10.1016/S0969-806X(01)00558-8

Li B, Wang X, Chen R, Huangfu W, Xie G (2008) Antibacterial activity of chitosan solution against Xanthomonas pathogenic bacteria isolated from Euphorbia pulcherrima. Carbohydr Polym 72(2):287–292. https://doi.org/10.1016/j.carbpol.2007.08.012

Li L, Ni R, Shao Y, Mao S (2014) Carrageenan and its applications in drug delivery. Carbohydr Polym 103(1):1–11. https://doi.org/10.1016/j.carbpol.2013.12.008

Liu S, Li L (2016) Thermoreversible gelation and scaling behavior of Ca2+-induced κ-carrageenan hydrogels. Food Hydrocoll 61:793–800

Liu J, Tian S, Meng X, Xu Y (2007) Effects of chitosan on control of postharvest diseases and physiological responses of tomato fruit. Postharvest Biol Technol 44(3):300–306. https://doi.org/10.1016/j.postharvbio.2006.12.019

Liu R, Jiang X, Guan H, Li X, Du Y, Wang P, Mou H (2009) Promotive effects of alginate-derived oligosaccharides on the inducing drought resistance of tomato. J Ocean Univ China 8(3):303–311. https://doi.org/10.1007/s11802-009-0303-6

Luan LQ, Hien NQ, Nagasawa N, Kume T, Yoshii F, Nakanishi TM (2003) Biological effect of radiation-degraded alginate on flower plants in tissue culture. Biotechnol Appl Biochem 38(3):283. https://doi.org/10.1042/ba20030058

Ma LJ, Li XM, Bu N, Li N (2010) An alginate-derived oligosaccharide enhanced wheat tolerance to cadmium stress. Plant Growth Regul 62(1):71–76. https://doi.org/10.1007/s10725-010-9489-2

Malerba M, Cerana R (2016) Chitosan effects on plant systems. Int J Mol Sci 17(7):1–15. https://doi.org/10.3390/ijms17070996

Meng X, Yang L, Kennedy JF, Tian S (2010) Effects of chitosan and oligochitosan on growth of two fungal pathogens and physiological properties in pear fruit. Carbohydr Polym 81(1):70–75. https://doi.org/10.1016/j.carbpol.2010.01.057

Mercier L, Lafitte C, Borderies G, Briand X, Esquerré-Tugayé MT, Fournier J (2001) The algal polysaccharide carrageenans can act as an elicitor of plant defence. New Phytol 149(1):43–51. https://doi.org/10.1046/j.1469-8137.2001.00011.x

Mollah MZI, Khan MA, Khan RA (2009) Effect of gamma irradiated sodium alginate on red amaranth (Amaranthus cruentus L.) as growth promoter. Radiat Phys Chem 78(1):61–64. https://doi.org/10.1016/j.radphyschem.2008.08.002

Morris CJ (2003) Carrageenan-induced paw edema in the rat and mouse. Methods Mol Biol *(Clifton, NJ) 225*:115–121. https://doi.org/10.1385/1-59259-374-7:115

Mousavi EA, Kalantari KM, Nasibi F, Oloumi H (2018) Effects of carrageenan as elicitor to stimulate defense responses of basil against Cuscuta campestris Yunck. Acta Bot Croat 77(1):62–69. https://doi.org/10.2478/botcro-2018-0005

Muley AB, Ladole MR, Suprasanna P, Dalvi SG (2019a) Intensification in biological properties of chitosan after γ-irradiation. Int J Biol Macromol 131:435–444. https://doi.org/10.1016/j.ijbiomac.2019.03.072

Muley AB, Shingote PR, Patil AP, Dalvi SG, Suprasanna P (2019b) Gamma radiation degradation of chitosan for application in growth promotion and induction of stress tolerance in potato (Solanum tuberosum L.). Carbohydr Polym 210(January):289–301. https://doi.org/10.1016/j.carbpol.2019.01.056

Naeem M, Idrees M, Aftab T, Khan MMA, Moinuddin, & Varshney, L. (2012a) Depolymerised carrageenan enhances physiological activities and menthol production in Mentha arvensis L. Carbohydr Polym 87(2):1211–1218. https://doi.org/10.1016/j.carbpol.2011.09.002

Naeem M, Idrees M, Aftab T, Khan MMA, Moinuddin, & Varshney, L. (2012b) Irradiated sodium alginate improves plant growth, physiological activities and active constituents in Mentha arvensis l. J Appl Pharm Sci 2(5):28–35. https://doi.org/10.7324/JAPS.2012.2529

Naeem M, Idrees M, Aftab T, Alam MM, Khan MMA, Uddin M, Varshney L (2015a) Radiation processed carrageenan improves plant growth, physiological activities, and alkaloids production in Catharanthus roseus L. Adv Bot 2015:1–11. https://doi.org/10.1155/2015/150474

Naeem M, Aftab T, Ansari AA, Idrees M, Ali A, Khan MMA, Uddin M, Varshney L (2015b) Radiolytically degraded sodium alginate enhances plant growth, physiological activities and alkaloids production in Catharanthus roseus L. J Radiat Res Appl Sci 8(4):606–616. https://doi.org/10.1016/j.jrras.2015.07.005

Necas J, Bartosikova L (2013) Carrageenan: a review. Vet Med 58(4):187–205. https://doi.org/10.17221/6758-VETMED

Pegg AM (2012) The application of natural hydrocolloids to foods and beverages. In: *Natural food additives, ingredients and flavourings*. Woodhead Publishing Limited, United Kingdom. https://doi.org/10.1533/9780857095725.1.175

Pichyangkura R, Chadchawan S (2015) Biostimulant activity of chitosan in horticulture. Sci Hortic 196:49–65. https://doi.org/10.1016/j.scienta.2015.09.031

Piculell L (1995) Gelling carrageenans. In: Food science and technology. Marcel Dekker, New York, pp 205–205

Pongprayoon W, Roytrakul S, Pichayangkura R, Chadchawan S (2013) The role of hydrogen peroxide in chitosan-induced resistance to osmotic stress in rice (Oryza sativa L.). Plant Growth Regul 70(2):159–173. https://doi.org/10.1007/s10725-013-9789-4

Qureshi AH (2010). *Effect of nitrogen and gamma-irradiated sodium alginate on the efficiency of beetroot (Beta vulgaris L.).* Doctoral dissertation, dissertation for the master degree. Aligarh: Aligarh Muslim University

Rabêlo VM, Magalhães PC, Bressanin LA, Carvalho DT, dos Reis CO, Karam D, Doriguetto AC, dos Santos MH, Filho S, P. R. dos S., & Souza, T. C. de. (2019) The foliar application of a mixture of semisynthetic chitosan derivatives induces tolerance to water deficit in maize, improving the antioxidant system and increasing photosynthesis and grain yield. Sci Rep 9(1):1–13. https://doi.org/10.1038/s41598-019-44649-7

Rı LA, Corpas FJ, Sandalio LM, Palma M, Go M, Barroso JB (2002) Reactive oxygen species, antioxidant systems and nitric oxide in peroxisomes. J Exp Bot 53(372):1255–1272

Rocha De Souza MC, Marques CT, Guerra Dore CM, Ferreira Da Silva FR, Oliveira Rocha HA, Leite EL (2007) Antioxidant activities of sulfated polysaccharides from brown and red seaweeds. J Appl Phycol 19(2):153–160. https://doi.org/10.1007/s10811-006-9121-z

Russo R, Malinconico M, Santagata G (2007) Effect of cross-linking with calcium ions on the physical properties of alginate films. Biomacromolecules 8(10):3193–3197. https://doi.org/10.1021/bm700565h

Sarfaraz A, Naeem M, Nasir S, Idrees M, Aftab T, Hashmi N et al (2011) An evaluation of the effects of irradiated sodium alginate on the growth, physiological activities and essential oil production of fennel (Foeniculum vulgare mill.). J Med Plant Res 5(1):15–21

Saucedo S, Contreras RA, Moenne A (2015) Oligo-carrageenan kappa increases C, N and S assimilation, auxin and gibberellin contents, and growth in Pinus radiata trees. J For Res 26(3):635–640. https://doi.org/10.1007/s11676-015-0061-9

Saucedo S, González A, Gómez M, Contreras RA, Laporte D, Sáez CA, Zúñiga G, Moenne A (2019) Oligo-carrageenan kappa increases glucose, trehalose and TOR-P and subsequently stimulates the expression of genes involved in photosynthesis, and basal and secondary metabolisms in Eucalyptus globulus. BMC Plant Biol 19(1):1–13. https://doi.org/10.1186/s12870-019-1858-z

Schmidt ÉC, Maraschin M, Bouzon ZL (2010) Effects of UVB radiation on the carragenophyte Kappaphycus alvarezii (Rhodophyta, Gigartinales): changes in ultrastructure, growth, and photosynthetic pigments. Hydrobiologia 649(1):171–182. https://doi.org/10.1007/s10750-010-0243-6

Shukla PS, Borza T, Critchley AT, Prithiviraj B (2016) Carrageenans from red seaweeds as promoters of growth and elicitors of defense response in plants. *Front Mar Sci 3*(MAY):1–9. https://doi.org/10.3389/fmars.2016.00081

Singh M, Khan MMA, Uddin M, Naeem M, Qureshi MI (2017) Proliferating effect of radiolytically depolymerized carrageenan on physiological attributes, plant water relation parameters, essential oil production and active constituents of Cymbopogon flexuosus Steud. Under drought stress. PLoS One 12(7):1–20. https://doi.org/10.1371/journal.pone.0180129

Tan H, Ma R, Lin C, Liu Z, Tang T (2013) Quaternized chitosan as an antimicrobial agent: antimicrobial activity, mechanism of action and biomedical applications in orthopedics. Int J Mol Sci 14(1):1854–1869. https://doi.org/10.3390/ijms14011854

Tripathi DK, Singh S, Singh VP, Prasad SM, Chauhan DK, Dubey NK (2016) Silicon nanoparticles more efficiently alleviate arsenate toxicity than silicon in maize Cultiver and hybrid differing in arsenate tolerance. Front Environ Sci 4(July). https://doi.org/10.3389/fenvs.2016.00046

Turk H (2019) Chitosan-induced enhanced expression and activation of alternative oxidase confer tolerance to salt stress in maize seedlings. Plant Physiol Biochem 141(June):415–422. https://doi.org/10.1016/j.plaphy.2019.06.025

Wang M, Chen Y, Zhang R, Wang W, Zhao X, Du Y, Yin H (2015) Effects of chitosan oligosaccharides on the yield components and production quality of different wheat cultivars (Triticum aestivum L.) in Northwest China. Field Crop Res 172:11–20. https://doi.org/10.1016/j.fcr.2014.12.007

Xing K, Chen XG, Li YY, Liu CS, Liu CG, Cha DS, Park HJ (2008) Antibacterial activity of oleoyl-chitosan nanoparticles: a novel antibacterial dispersion system. Carbohydr Polym 74(1):114–120. https://doi.org/10.1016/j.carbpol.2008.01.024

Xu M, Kreeger PK, Shea LD, Woodruff TK (2006) Tissue-engineered follicles produce live, fertile offspring. Tissue Eng 12(10):2739–2746. https://doi.org/10.1089/ten.2006.12.2739

Xu J, Zhao X, Han X, Du Y (2007) Antifungal activity of oligochitosan against Phytophthora capsici and other plant pathogenic fungi in vitro. Pestic Biochem Physiol 87(3):220–228. https://doi.org/10.1016/j.pestbp.2006.07.013

Yan N, Chen X (2015) Sustainability: don't waste seafood waste. Nat News 524(7564):155

Yen MT, Yang JH, Mau JL (2009) Physicochemical characterization of chitin and chitosan from crab shells. Carbohydr Polym 75(1):15–21. https://doi.org/10.1016/j.carbpol.2008.06.006

Zehra A, Choudhary S, Mukarram M, Naeem M, Khan MMA, Aftab T (2020) Impact of long-term copper exposure on growth, photosynthesis, antioxidant defence system and Artemisinin biosynthesis in soil-grown Artemisia annua genotypes. Bull Environ Contam Toxicol 104(5):609–618. https://doi.org/10.1007/s00128-020-02812-1

Zeng L, Qin C, Wang W, Chi W, Li W (2008) Absorption and distribution of chitosan in mice after oral administration. Carbohydr Polym 71(3):435–440. https://doi.org/10.1016/j.carbpol.2007.06.016

Zhang X, Li K, Xing R, Liu S, Chen X, Yang H, Li P (2018) MiRNA and mRNA expression profiles reveal insight into chitosan-mediated regulation of plant growth. J Agric Food Chem 66(15):3810–3822. https://doi.org/10.1021/acs.jafc.7b06081

Zhou G, Sun YP, Xin H, Zhang Y, Li Z, Xu Z (2004) In vivo antitumor and immunomodulation activities of different molecular weight lambda-carrageenans from Chondrus ocellatus. Pharmacol Res 50(1):47–53. https://doi.org/10.1016/j.phrs.2003.12.002

Zia KM, Tabasum S, Nasif M, Sultan N, Aslam N, Noreen A, Zuber M (2017) A review on synthesis, properties and applications of natural polymer based carrageenan blends and composites. Int J Biol Macromol 96:282–301. https://doi.org/10.1016/j.ijbiomac.2016.11.095

Zou P, Li K, Liu S, Xing R, Qin Y, Yu H, Zhou M, Li P (2015) Effect of chitooligosaccharides with different degrees of acetylation on wheat seedlings under salt stress. Carbohydr Polym 126:62–69. https://doi.org/10.1016/j.carbpol.2015.03.028