



# Carrageenans from Red Seaweeds As Promoters of Growth and Elicitors of Defense Response in Plants

Pushp S. Shukla<sup>1</sup>, Tudor Borza<sup>1</sup>, Alan T. Critchley<sup>2</sup> and Balakrishnan Prithiviraj<sup>1\*</sup>

<sup>1</sup> Marine Bioproducts Research Laboratory, Department of Environmental Sciences, Dalhousie University, Truro, NS, Canada,

<sup>2</sup> Acadian Seaplants Limited, Research and Development, Dartmouth, NS, Canada

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### \*Correspondence:

Balakrishnan Prithiviraj  
bprithiviraj@dal.ca

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Plants incessantly encounter abiotic and biotic stresses that limit their growth and productivity. However, conversely, plant growth can also be induced by treatments with various abiotic and biotic elicitors. Carrageenans are sulfated linear polysaccharides that represent major cellular constituents of seaweeds belonging to red algae (*Rhodophyta*). Recent research has unraveled the biological activity of carrageenans and of their oligomeric forms, the oligo carrageenans (OCs), as promoters of plant growth and as elicitors of defense responses against pests and diseases. In this review, we discuss the molecular mechanisms by which carrageenans and OCs mediate plant growth and plant defense responses. Carrageenans and OCs improve plant growth by regulating various metabolic processes such as photosynthesis and ancillary pathways, cell division, purine and pyrimidine synthetic pathways as well as metabolic pathways involved in nitrogen and sulfur assimilation. Carrageenans and OCs also induce plant defense responses against viroids, viruses, bacteria, fungi and insects by modulating the activity of different defense pathways, including salicylate, jasmonate and ethylene signaling pathways. Further studies will likely substantiate the beneficial effects of carrageenans and of OCs on plant growth and plant defense responses and open new avenues for their use in agriculture and horticultural industry.

**Keywords:** carrageenans, plant elicitor, plant growth, plant defense mechanisms, plant signaling pathways, systemic acquired resistance, induced resistance

## INTRODUCTION

Marine organisms such as bacteria, microalgae and seaweeds constitute approximately one-half of the global biodiversity and thus, the oceans represent an enormous source of functional compounds produced by these biological systems, including various polysaccharides (Courtois, 2009; de Jesus Raposo et al., 2013, 2015; Ahmadi et al., 2015), polyunsaturated fatty acids (PUFA) (Russell and Nichols, 1999), vitamins, anti-oxidants (Rocha de Souza et al., 2007), enzymes and bioactive peptides (Campo et al., 2009; Shahidi and Ambigaipalan, 2015). Since many of the habitats of marine organisms are harsher, more diverse and extremely competitive as compared to those of terrestrial organisms, they adapted to produce a wide range of unique molecules that are essential for their survival (Vo and Kim, 2010).

Seaweeds are multicellular marine macroalgae found in all coastal ecosystems of the world, with essential roles in maintaining the biodiversity of the in-shore marine environment (Sangha et al., 2014). These algae have long been used in the human nutritional regime as a source of unique

carbohydrates. Currently, three carbohydrate polymers from seaweeds are commercially exploited: agar and carrageenans from red seaweeds and alginates from brown seaweeds (Campo et al., 2009). Carrageenans are represented by a number of naturally occurring anionic sulfated linear polysaccharides present in a variety of red algae (*Rhodophyta*). The term carrageenan is derived from an Irish word, “carrageen” meaning a “little rock” (Campo et al., 2009). Carrageenans found their way in a large number of commercial applications such as food and dairy industry (Prajapati et al., 2014) and drug delivery (Li et al., 2014). In addition to these applications, carrageenans were shown to possess several properties that are of interest for the pharmaceutical industry including antiviral, antitumor, immunomodulatory, antihyperlipidemic and anticoagulant activities (Yuan et al., 2006; Campo et al., 2009; Prajapati et al., 2014; Ahmadi et al., 2015). Carrageenans were also shown to have antioxidant activity by scavenging hydrogen peroxide (Sun et al., 2010). The effects of carrageenans on mammalian systems were examined in several reviews (Campo et al., 2009; Courtois, 2009; Vo and Kim, 2010; de Jesus Raposo et al., 2013, 2015; Prajapati et al., 2014; Ahmadi et al., 2015). More recently, carrageenans were tested for their effects on plant growth and for their roles in enhancing plant immunity. Though the information on the effects of carrageenans on plant systems is still rather limited, in this review we discuss the advancements in this field of research, focusing on the molecular mechanisms through which carrageenans promote plant growth and induce plant defense responses, resulting in increased plant productivity and protection.

## STRUCTURE AND SOURCES OF CARRAGEENANS

Carrageenans are linear, partially hydrophilic sulfated galactans formed by alternate units of D-galactose and 3, 6-anhydro-galactose joined by  $\alpha$ -1, 3 and  $\beta$ -1, 4-glycosidic linkage (Prajapati et al., 2014). These polysaccharides are traditionally split into six basic types: iota ( $\iota$ -), kappa ( $\kappa$ -), lambda ( $\lambda$ -), mu ( $\mu$ -), nu ( $\nu$ -), and theta ( $\theta$ )-carrageenans (Campo et al., 2009).  $\kappa$ -carrageenan consists of D-galactose having sulfate at C4 position linked to anhydro-galactose (Vera et al., 2011) and is commercially extracted from the red alga *Kappaphycus alvarezii* through a hot extraction process. Beta ( $\beta$ )-carrageenan is similar to  $\kappa$ -carrageenan but lacks the sulfate on C4 of the 1, 3-linked units.  $\lambda$ -carrageenan is formed by D-galactose having the sulfate group at C2 position linked to a D-galactose sulfated at C2 and C6 position.  $\lambda$ -carrageenan is more hydrophilic than  $\kappa$ -carrageenan and it is obtained from the red algae of the genera *Gigartina* and *Chondrus* by drum dryer or alcohol precipitation process (Vera et al., 2011; Prajapati et al., 2014).  $\iota$ -carrageenan is obtained mainly from *Euclima denticulatum* by the freeze thaw or gel process and it is composed of D-galactose having the sulfate group at C4 position linked to anhydrogalactose sulfated at C2 positions (Vera et al., 2011; Prajapati et al., 2014). Sulfate content in carrageenans varies from 20% in  $\kappa$ -carrageenan to 33% in  $\iota$ -carrageenan and to 41% in  $\lambda$ -carrageenan.

## EFFECT OF CARRAGEENANS ON PLANT GROWTH AND PLANT DEFENSE

### Plant Growth

Green land plants are autotrophic, immobile and hardy organisms. They evolved various complex metabolic pathways to capture energy and synthesize metabolites required for their growth and development (Yu et al., 2015). Carrageenans and oligo carrageenans (OCs) stimulate the growth of green land plants by modulating various physiological and biochemical processes. OCs are oligomers of sulfated galactose, generally 20 units long, prepared through depolymerization by hot, acid hydrolysis of the commercially available  $\kappa$ -,  $\lambda$ -, and  $\iota$ -carrageenans. OCs appear to act as signal molecules, enhancing the induction of microspore embryogenesis in *Brassica oleracea* var. *italica* (Lemonnier-Le Penhuizic et al., 2001). The efficiency of OCs in inducing microspore embryogenesis increased with the increase in the number of sulfate substituents (from  $\kappa$ - to  $\lambda$ -carrageenan). In combination with heat stress,  $\lambda$ -carrageenan significantly enhanced the production of *B. oleracea* var. *italica* microspore-derived embryos (Lemonnier-Le Penhuizic et al., 2001). OCs were also shown to augment plant height and leaf biomass in tobacco by stimulating photosynthesis and carbon fixation in plants including enhanced ribulose 1, 5 bisphosphate carboxylase/oxygenase (Rubisco) activity (Muñoz et al., 2011). Similarly, Castro et al. (2012) found that spraying  $\kappa$ -,  $\lambda$ -, and  $\iota$ -OCs on tobacco leaves increased plant height, leaf biomass, chlorophyll content, and enhanced net photosynthesis through higher PSII activity. Tobacco plants also showed improved carbon fixation and nitrogen assimilation. Rubisco and other enzymes involved in the basal metabolism such as glutamate dehydrogenase, pyruvate dehydrogenase, isocitrate dehydrogenase, inosine monophosphate dehydrogenase and glucose 6-phosphate dehydrogenase displayed higher activity. The activation of NADP(H)-synthesizing enzymes may determine an overall increase in the intracellular content of NADP(H) and a modified redox state. As a result, it has been suggested that the reducing condition probably promoted photosynthesis and ancillary processes (Castro et al., 2012). Saucedo et al. (2015) found that the application of OCs improved the growth of *Pinus radiata* by inducing the accumulation of C, N, and S. OCs treated plants showed increased activity of several NAD(P)H-synthesizing enzymes involved in the basal metabolism. Similarly, Bi et al. (2011) found that  $\kappa$ -carrageenan initiates early flowering and improves growth in chickpea and maize by increasing plant height, the number of pods in chickpea and leaves in both plants. Spray applications of  $\kappa$ -,  $\lambda$ - and  $\iota$ -OCs resulted in increased plant growth and cell division in tobacco and these changes were associated with increased cell number but not cell size. The transcript levels of cyclins A and B and of CDKs A and B were found to be increased by the applications of OCs (Castro et al., 2012). Therefore, it has been suggested that the increased biomass is caused by OCs' modulating effects on the expression of cell cycle regulatory proteins (Castro et al., 2012; González et al., 2013a).

*Eucalyptus globulus* plants treated with carrageenans showed an increase in height and trunk diameter (González et al.,

2013b).  $\kappa$ - and  $\iota$ -carrageenan caused a 58 and 47% increase in plant height, respectively, and a 44 and 40% increase in trunk diameter, respectively. In addition to changes in growth parameters, *E. globulus* treated with OCs had increased amounts of holocellulose,  $\alpha$ -cellulose and essential oils. OCs also altered the levels of polyphenolic compounds such as genistein, rutin, ellagic acid, morin, luteolin, and quercetin that have potential antimicrobial activities in *E. globulus* (González et al., 2013b). The mechanisms through which  $\kappa$ -carrageenan mediated the growth of *E. globulus* were also analyzed by González et al. (2014a). It has been suggested that  $\kappa$ -carrageenan improved the growth of *E. globulus* by regulating a plethora of cellular processes that are subjected to continuous environmental changes; these variations can determine large fluctuations in the redox state.  $\kappa$ -OC improved the redox status of *E. globulus* by inducing the synthesis of reduced nicotinamide adenine dinucleotide phosphate (NADPH), of ascorbate (ASC) and glutathione (GSH), and of thioredoxin reductase (TRR) activity, and likely modulated the crosstalk between various biological processes, leading to improved plant growth (González et al., 2014a). NAD<sup>+</sup> and NADP<sup>+</sup> are essential reducing compounds for the plant growth as co-factors of enzymes involved in electron transport and metabolic processes (Hashida et al., 2009). OCs increased the NADPH levels, which are involved in regulating the basal metabolism through TRRs/thioredoxins (TRXs) system. In presence of elevated levels of NADPH the TRR/TRX system reduces the disulfide residues of many key metabolic enzymes modulating, therefore, various pathways (González et al., 2014a). ASC and GSH play important roles in the cell cycle during the transition from G1 to S phase (Liso et al., 1988; Noctor and Foyer, 1998; de Pinto et al., 1999; Vernoux et al., 2000). In addition to cell cycle regulation, GSH may also regulate photosynthesis, growth and carbon assimilation (Jiang et al., 2012). Thus,  $\kappa$ -OC applications appear to affect NADPH, ASC, and GSH synthesis and the activity of TRR/TRX systems, also influencing processes such as photosynthesis, cell division, Krebs cycle, purine and pyrimidine biosynthetic pathways as well as other metabolic pathways involved in C, N, and S assimilation (Gelhay et al., 2005; Montrichard et al., 2009; González et al., 2014a).

$\kappa$ -OC was shown to induce the synthesis of plant growth hormones such as indole-3-acetic acid (IAA), gibberellic acid (GA<sub>3</sub>) and trans-zeatin by activating the TRR/TRX system and altering the redox status of plant cells (González et al., 2014b). Similarly, Saucedo et al. (2015) found that  $\kappa$ -OC increased the levels of IAA and GA<sub>3</sub>, promoting the growth of *Pinus radiata*. Though data is still limited these studies indicate that carrageenans can improve plant growth by regulating phytohormone synthesis.

In addition to promoting plant growth, the application of  $\kappa$ -OC also improved the economic value of *Eucalyptus* by reprogramming its terpenoid metabolism. Treatment of *Eucalyptus* with  $\kappa$ -OC kappa was found to reduce the synthesis of six terpenoids and to increase the level of 12 other terpenoids (González et al., 2014c). Among the terpenoids shown to be down-regulated were monoterpenoids from the limonene family (eucalyptol, sabinene, and  $\alpha$ -terpineol) and pinene family

( $\alpha$ -pinene), a sesquiterpenoid of the cadinene family ( $\delta$ -cadinene) and of the isolekene family (isolekene). The terpenoids whose expression was up-regulated by  $\kappa$ -OC were monoterpenoids of the limonene family (silvestrene,  $\alpha$ -phellandrene,  $\gamma$ -terpinene, limonene oxide) and pinene family ( $\beta$ -pinene), a sesquiterpenoid of the cadinene family ( $\gamma$ -cadinene), several of the isolekene family (aromadendrene, viriflorene,  $\alpha$ -gurjunene,  $\gamma$ -gurjunene,  $\alpha$ -guaiene), and a linear monoterpene (myrcene).  $\kappa$ -OC also conferred defense against insects and microbes in *Eucalyptus* by increasing the synthesis of the monoterpene  $\gamma$ -terpinene (González et al., 2014c). Overall, by changing the redox status and by activating the TRR/TRX system,  $\kappa$ -OC reprogrammed terpenoid metabolism with noticeable effects on the secondary metabolism of *Eucalyptus* trees (González et al., 2014c). Therefore, in some cases,  $\kappa$ -OC can influence secondary metabolism regulation with beneficial effects on plant growth. The effects of various types of carrageenans on plant growth are summarized in **Table 1** and **Figure 1**.

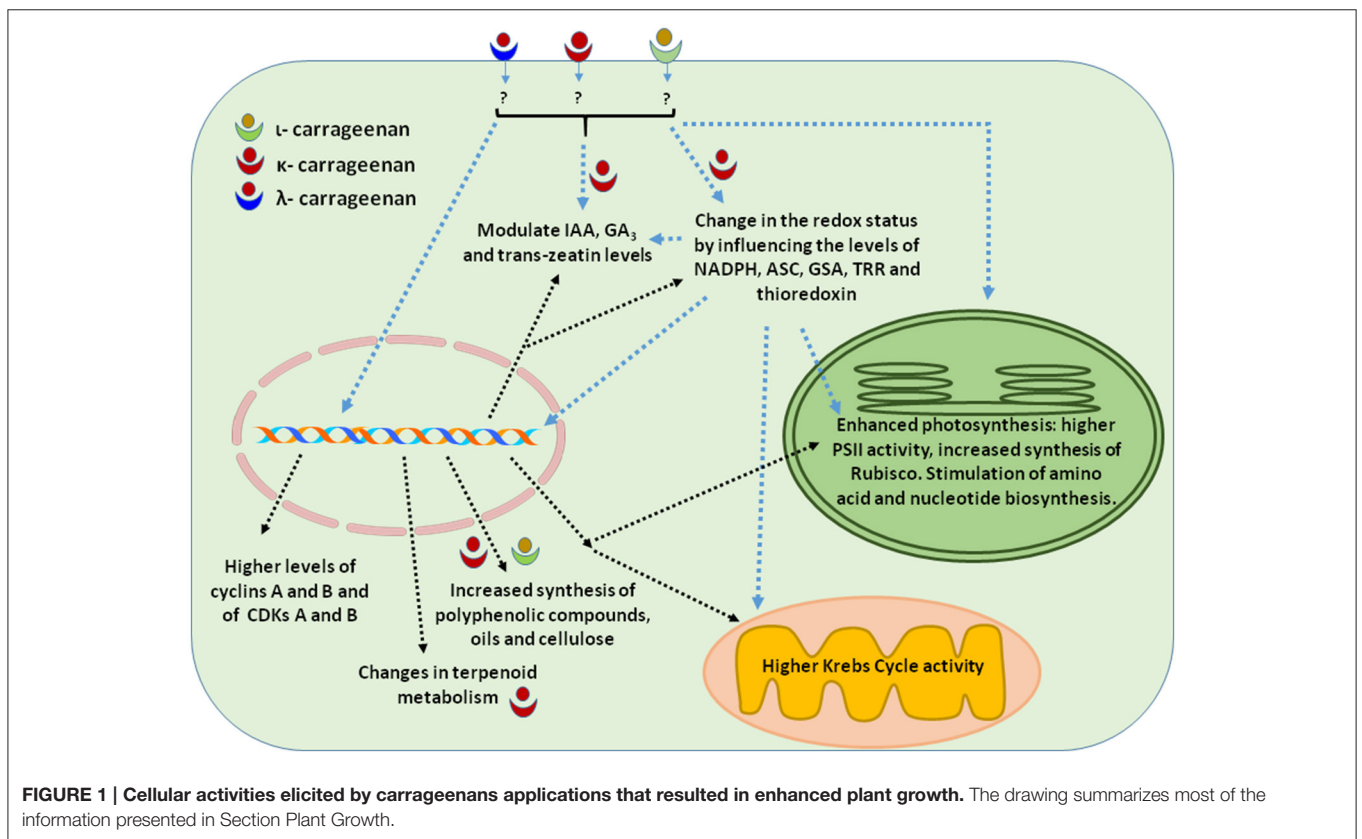
## Plant Defense

Green land plants are attacked by a multitude of organisms including insects and pathogens such as viruses, bacteria and fungi (Pieterse and Dicke, 2007; Stadnik and De Freitas, 2014). These pathogens impair plant growth and productivity. Plants deploy a wide range of defense mechanisms against pathogens. As plants do not have specialized defense cells and are devoid of a somatic adaptive immune system, plant's immunity relies on the capacity of every cell to detect pathogens and activate defense responses (Jones and Dangl, 2006; Nicaise, 2015). Plants follow either constitutive or inducible defense mechanisms to prevent pathogen ingress (Pieterse and Dicke, 2007). Plants challenged by a pathogen or under insect attack respond through a series of molecular events, including the synthesis of different responsive alarm signals that activate the salicylate (SA), jasmonate (JA) and ethylene (ET) signaling pathways that are part of plant's primary defense response (Koornneef and Pieterse, 2008). Depending on the type of attack, the crosstalk between these signaling pathways determines the plant defense tactics. SA mediated defense responses play a central role in systemic acquired resistance, which occurs mainly against biotrophic pathogens, involving the activation of pathogenesis-related (PR) proteins. JA and ET pathways are required mainly for the induction of nonspecific disease resistance (Dixon et al., 1994; Dong, 1998; Scheel, 1998; Shah, 2003; Maffei et al., 2007; Thaler et al., 2012; Fu and Dong, 2013).

Plant defense responses can be induced by pathogen's cell wall components including chitin, lipo-polysaccharides, proteins such as bacterial flagellin and other chemicals of natural and synthetic origin like chitosan, salicylic acid, jasmonic acid, isonicotinic acid, and benzothiadiazole (Dixon et al., 1994; Mercier et al., 2001; Bektas and Eulgem, 2015; Iriti and Varoni, 2015). Compounds that induce plant defense responses are known as elicitors. These molecules confer protection against pathogens by binding to specific receptors located in the plasma membrane of plants and trigger defense responses by inducing a plethora of genes involved in defense mechanisms (Vera et al., 2011).

**TABLE 1 | Role of carrageenans in plant growth promotion.**

	Type of carrageenan	Source	Response	References
1.	$\kappa$ -	<i>Hypnea musciformis</i>	Promote growth of chickpea and maize by eliciting the production of secondary metabolites	Bi et al., 2011
2.	$\kappa$ -OC	Commercially available	Stimulates growth and basal metabolism and increases the level of growth-promoting hormones in <i>Pinus radiata</i>	Saucedo et al., 2015
3.	$\kappa$ , $\beta$ , and $\iota$ -OC	Commercially available	Improves growth of tobacco by enhancing net photosynthesis and ribulose 1, 5 biphosphate carboxylase/oxygenase activity	Muñoz et al., 2011
4.	$\kappa$ , $\beta$ , and $\iota$ -OC	Commercially available	Stimulates the growth of tobacco by enhancing photosynthesis and basal metabolism	Castro et al., 2012
5.	$\kappa$ , $\beta$ , and $\iota$ -OC	Commercially available	Increases photosynthesis, basal metabolism, essential oils, polyphenolic compounds and growth of <i>Eucalyptus globulus</i>	González et al., 2013a,b, 2014a



Epidemics of infectious disease are rarely observed in the natural seaweed populations, indicating that during the course of evolution these plants have developed efficient defense mechanism against different pathogens (Potin et al., 1999). These seaweeds serve as a source for a large number of compounds such as laminarin, fucans, ulvans, and carrageenans, which all act as elicitor molecules against pathogens (Mercier et al., 2001; Klarzynski et al., 2003; Sangha et al., 2010; Vera et al., 2011).

Carrageenans and the OCs derived from them act as elicitors and activate defense mechanism against plant pathogens (Stadnik and De Freitas, 2014); probably this activity depends on the degree of sulfation (Sangha et al., 2010, 2015). Viroids belonging to Pospiviroidae and Avsunviroidae families are causing more than two dozens of diseases in agricultural, horticultural and

ornamental plants (Singh and Teixeira da Silva, 2006). Viroids replicate in the nucleus or chloroplasts from where they can be transferred from cell to cell through plasmodesmata and, for longer distances, through phloem, to eventually establish systemic infections (Ding, 2009). Carrageenans have been shown to elicit resistance against viroids in plants (Sangha et al., 2015).  $\lambda$ -carrageenan treated tomato plants showed higher resistance against Tomato Chlorotic Dwarf Viroid (TCDVd), a devastating pathogen of a large number of plants (Singh et al., 2006; Sangha et al., 2015). TCDVd transcript abundance was relatively higher in the water treated plants as compared to  $\lambda$ -carrageenan treated tomato plants. This result implies that  $\lambda$ -carrageenans exhibit suppressive effects on TCDVd in tomato plants, likely by controlling viroid replication (Sangha



et al., 2015). Proteomic analysis of  $\lambda$ -carrageenan treated plants in the presence of TCDVd infection revealed differences in the abundance of 14 proteins with different cellular functions. These results suggest that the reduction of viroid infection was primarily due to biochemical changes that occurred in plants. The up-regulation of lipoxygenase (*LOX*), allene oxide synthase (*AOS*) and pathogenesis-related proteins in TCDVd infected tomatoes indicates a possible role of JA response in plant's resistance against viroid infection (Sangha et al., 2015). Carrageenans are selective inhibitors of several enveloped and non-enveloped viruses in plants and animals (González et al., 1987; Vera et al., 2011; Wang et al., 2012; Kalitnik et al., 2013) and act predominantly by inhibiting the binding or internalization of viral particles into the host cells (Ahmadi et al., 2015). Nagorskaya et al. (2008) reported that  $\kappa/\beta$ -carrageenan from the red marine alga *Tichocarpus crinitus* reduced the infection of tobacco leaves by the tobacco mosaic virus (TMV). Carrageenans conferred their antiviral activity on plants as well as on the virus itself (Nagorskaya et al., 2008). Also, the treatment with  $\kappa/\beta$ -carrageenan from *T. crinitus* stimulated, to some extent, several lytic processes in *Datura stramonium*, preventing the intracellular accumulation and translocation of Potato Virus X particles (Nagorskaya et al., 2010). Sulfated Polysaccharide 4 (SPS4), containing 98%  $\kappa$ -carrageenan and extracted from the red alga *Hypnea musciformis*, was found to reduce the TMV infection in tobacco plants (Ghannam et al., 2013). Molecular analysis of SPS4 induced antiviral activity revealed that the expression of SA-dependent defense related genes *PR1a* (encoding an antimicrobial protein), *PR2* (1, 3-glucanase), and *PR5* (thaumatin-like antimicrobial protein) was increased. The expression of JA pathway-dependent genes such as *PR3* (encoding a basic chitinase) and *Def1.2* (encoding a defensin) were also found to be enhanced (Ghannam et al., 2013). Thus, SPS4 modulates defense response in tobacco plants by inducing the crosstalk between the SA and JA-dependent signaling pathways.

$\iota$ -,  $\kappa$ -, and  $\lambda$ -oligo carrageenans were found to provide tobacco plants enhanced protection against tobacco mosaic virus (TMV), *Pectobacterium carotovorum* and *Botrytis cinerea* likely due to a sustained induction of phenylalanine ammonia lyase activity which determined the accumulation of phenylpropanoid compounds with potential antimicrobial activities (Vera et al., 2012). Patier et al. (1995) showed that  $\kappa$ -OC prepared by the enzymatic hydrolysis of  $\kappa$ -carrageenan elicits laminarinase activity in *Rubus fruticosus* cells, and this activity is known to be involved in plant defense. Mercier et al. (2001) reported that  $\lambda$ -carrageenan proved to be the most potent elicitor molecule because of its high sulfate content, as compared to that of  $\iota$ - and  $\kappa$ -carrageenan.  $\lambda$ -carrageenan induced systemic resistance against *Phytophthora parasitica* var. *nicotianae* in tobacco cells by increasing the expression of a sesquiterpene cyclase involved in the synthesis of the phytoalexin capsidiol, of a basic chitinase (*PR3* family), and of a type II proteinase inhibitor. The expression of lipoxygenase (*LOX*) and of ACC oxidase (*ACO*), whose gene expression leads to JA and ET biosynthesis, was also found to be induced, and the amount of cellular SA to be increased. In contrast to this report, Sangha et al. (2010), showed

$\lambda$ -carrageenan triggered a differential resistance to *Sclerotinia sclerotiorum* infection in *Arabidopsis thaliana*, largely by a JA dependent mechanism. Notably, *S. sclerotiorum* requires the secretion of oxalic acid to infect the plant by suppressing the oxidative burst of the host plant (Cessna et al., 2000). Sangha et al. (2010) showed that  $\lambda$ -carrageenan treatment reduces the oxalic acid concentration in *Arabidopsis* plants by increasing the *in planta* oxalate oxidase activity providing, therefore, an explanation for the reduced susceptibility to *S. sclerotiorum*. The expression of the *PR3*, *PDF1.2* (Plant Defensin 1.2) and *AOS* genes involved in the defense response were induced in the  $\lambda$ -carrageenan treated plants. Higher levels of *AOS* correlate with increased biosynthesis of JA (Laudert and Weiler, 1998) and with a strong up-regulation of JA responsive gene *PDF1.2*, which has antifungal properties (Sangha et al., 2010).  $\lambda$ -carrageenan induced resistance against *S. sclerotiorum* in salicylic acid deficient mutant of *A. thaliana* (*ics1*), but did not rescue the susceptibility *jar1* (JA deficient) mutant, suggesting that  $\lambda$ -carrageenan activates only the JA dependent pathway and not the SA dependent pathway. However, these responses against *S. sclerotiorum* were not observed in *Arabidopsis* treated with  $\iota$ -carrageenan (Sangha et al., 2010). Thus, the application of carrageenans elicits JA signaling pathway in most plants and the SA signaling pathway in some plants but the level of activation seems to be influenced by the type of carrageenans used in treatments as well as by the plant model used in experiments.

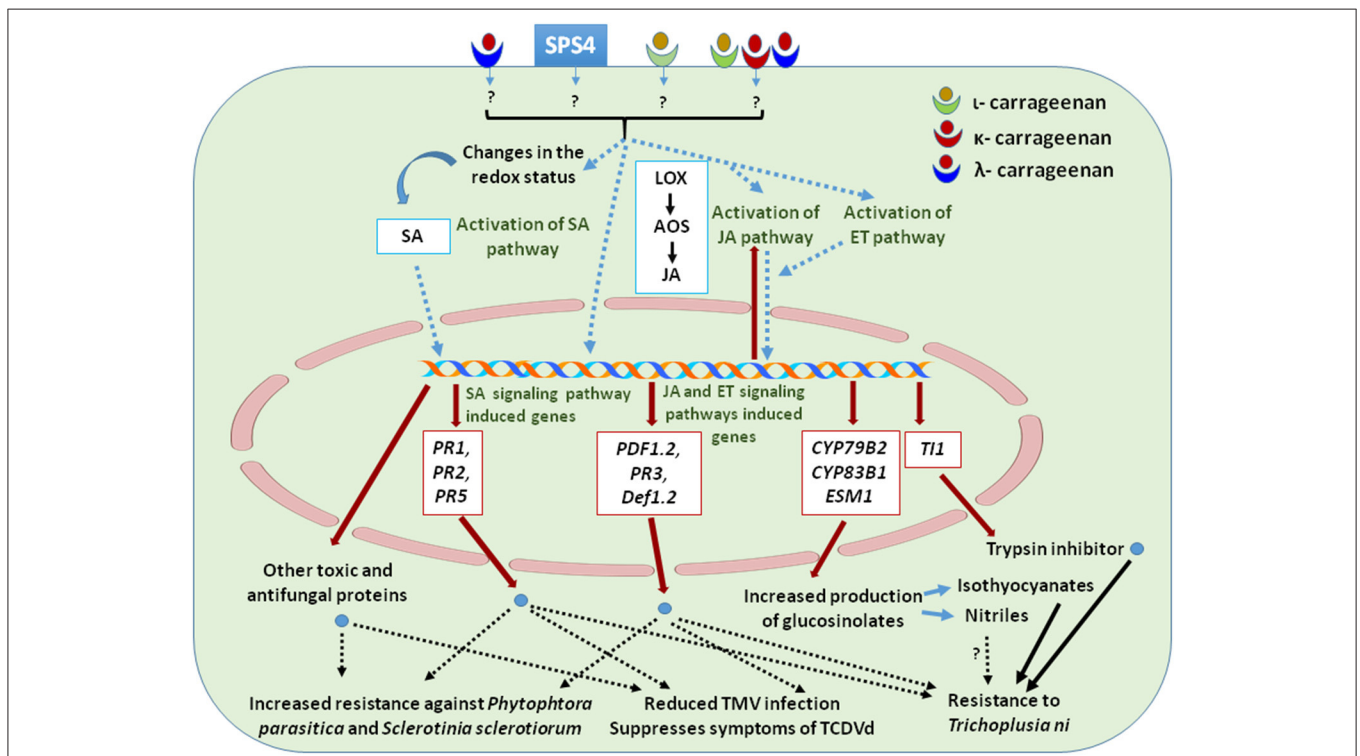
While the protective effects of carrageenans against viroids, viruses, bacteria, and fungi are rather well documented, not much information is available on the role of carrageenans in defense response against insects. Sangha et al. (2011) reported that carrageenans act as elicitor of defense responses in *Arabidopsis* against the insect *Trichoplusia ni* (cabbage looper), which is a polyphagous herbivore that feeds on a number of plant species including *Arabidopsis* (Jander et al., 2001). *T. ni* affects various *Arabidopsis* ecotypes differently and shows specific sensitivity to different plant glucosinolates, defense signaling pathways and proteinase inhibitors (Jander et al., 2001; Zhang et al., 2006). Sangha et al. (2011) showed that foliar application of  $\iota$ - and  $\kappa$ -carrageenans on *Arabidopsis* reduced the leaf damage caused by *T. ni* as compared to those treated with  $\lambda$ -carrageenan and control. On the 10th day of *T. ni* infestation, inhibition of larval growth was greater in the  $\kappa$ -carrageenan treated than in the  $\iota$ -carrageenan treated plants while  $\lambda$ -carrageenan had no effect (Sangha et al., 2011). Adaptation of plants in response to insect invasion includes induced biochemical responses which regulate the expression of defense related genes and, hence, the production of secondary metabolites and proteins including toxins, antifeedants and anti-nutrients (Walling, 2000; Zangerl, 2003). *Arabidopsis* plants treated with  $\iota$ -carrageenan showed higher expression of JA and SA responsive genes *PDF1.2* and *PR1*, respectively. SA and JA deficient mutant *ics1* and *jar1* are susceptible to *T. ni* infestation in the presence of carrageenan, suggesting that both SA and JA dependent pathways are involved in the carrageenan induced *Arabidopsis* resistance against *T. ni* (Sangha et al., 2011). Thus,  $\iota$ -carrageenan mediates the cross-talk between defense signaling pathways and induced plant resistance toward *T. ni* by regulating different biochemical pathways. Plant

defense mechanisms against herbivores comprise the synthesis of various anti-feedant proteinase inhibitors such as trypsin inhibitor protein 1 (*T11*) (Ryan, 1990; Broadway, 1995). These proteins inhibit several insect digestive proteases and ultimately determine reduced insect growth rate or, in more severe cases, increased mortality due to reduced nutrient uptake (Ryan, 1990).  $\iota$ -carrageenan enhanced the expression of *T11*, which indeed led to reduced larval growth and development in  $\iota$ -carrageenan

treated plants as compared to healthy control larvae. More feeding damage was observed on  $\lambda$ -carrageenan treated plant which did not show a stimulation of *T11* gene expression while  $\kappa$ -carrageenans had some inhibitory effects on larval growth and development in spite of limited *T11* induction (Sangha et al., 2011). In addition to this,  $\iota$ -carrageenan was found to induce the expression of genes involved in indole glucosinolate biosynthesis including that of *CYP79B2* and *CYP83B1* that were associated

**TABLE 2 | Role of carrageenans in plant defense.**

Type of carrageenan	Source	Response	References
1. $\kappa/\beta$ -	<i>Tichocarpus crinitus</i>	Less necrotic lesions on the tobacco leaves inoculated with tobacco mosaic virus.	Nagorskaya et al., 2008
2. $\kappa/\beta$ -	<i>Tichocarpus crinitus</i>	Reduced Potato Virus X infection of <i>Datura stramonium</i> leaves.	Nagorskaya et al., 2010
3. $\kappa$ -	<i>Hypnea musciformis</i>	SPS4, $\kappa$ -carrageenan, enhances immunity of tobacco in response to tobacco mosaic virus by inducing salicylic, jasmonic and ethylene-dependent defense pathways.	Ghannam et al., 2013
4. $\lambda$ -	Source unknown	Confers resistance to <i>Arabidopsis thaliana</i> against <i>Sclerotinia sclerotiorum</i> fungal infection by inducing the expression of jasmonic acid related genes.	Sangha et al., 2010
5. $\lambda$ -	<i>Gigartina acicularis</i> and <i>Gigartina pistillata</i>	Elicitor of plant defense response against <i>Phytophthora parasitica</i> .	Mercier et al., 2001
6. $\iota$ -	Source unknown	Confers resistance to <i>Arabidopsis thaliana</i> against the moth <i>Trichoplusia ni</i> by regulating the expression of defense related genes.	Sangha et al., 2011
7. $\iota$ -	Source unknown	Induces tomato defense against Tomato Chlorotic Dwarf Viroid (TCDVd) by regulating jasmonic acid mediated signaling pathway.	Sangha et al., 2015
8. Oligo	Source unknown	Systemically induce the suppression of viral, bacterial and fungal infections in tobacco by enhancing the accumulation of phenylpropanoids.	Vera et al., 2012



**FIGURE 2 | Cellular functions and signaling pathways involved in defense mechanisms elicited by carrageenans applications that resulted in increased resistance to pathogens.** The drawing summarizes most of the information presented in Section Plant Defense.

with a prominent phenotypic effect on *T. ni* larva (Sangha et al., 2011). Glucosinolates have essential roles in defense responses as they can be easily converted to volatile compounds that have been shown to affect the performance of various herbivores. Up-regulation of glucosinolate biosynthesis genes, in the presence of  $\iota$ -carrageenan, suggests that these elicitors can regulate the biosynthesis of glucosinolates, conferring carrageenan-induced resistance to *T. ni* larva but not to adults (Jander et al., 2001; Lambrix et al., 2001; Sangha et al., 2011). The expression of Epithiospecifer Modifier 1 (*ESM1*), a gene involved in glucosinolate hydrolysis and isothiocyanates production, was also increased in the  $\iota$ -carrageenan treated plants, causing further damage to *T. ni* herbivory (Zhang et al., 2006; Sangha et al., 2011). The effects of carrageenans on plant resistance against various pathogens are summarized in **Table 2** and **Figure 2**.

In conclusion, the use of carrageenans in agriculture represents a promising approach for improving plant growth and for inducing plant defense mechanisms. Large scale, field based applications of carrageenans are needed to validate their

effects on plant growth and resistance against various pathogens. Additional, more comprehensive and systematic studies of their functions, at molecular level, in model plant systems such as *Arabidopsis*, are required to further decipher their mode of action. These approaches may lead to the discovery of green plant target molecules that interact with carrageenans and reveal novel regulatory interactions controlling plant growth and defense mechanisms. The detailed study of carrageenans as promoters of plant growth and elicitors of resistance to pathogens may lead to the development of multifunctional crop protectants, conferring resistance against a broad spectrum of plant pathogens as well as better crop yields.

## AUTHOR CONTRIBUTIONS

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**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The Review Editor BJ declares that, despite having been supervisor of author PS, the review process was handled objectively and no conflict of interest exists.

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