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Application of marine-derived polysaccharides as immunostimulants in aquaculture: A review of current knowledge and further perspectives

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ABSTRACT

The use of antibiotics in the feeds of cultivable aquatic animals has been generally practised to reduce infectious diseases as well as to improve the survival and growth. In recent years, many countries ban to aquatic animals due to the use of large amount of antibiotics and chemotherapies, thus alternative novel strategies are need to promote the growth of aquatic animals and control the pathogens. Dietary supplementation of marine-derived polysaccharides (MDPs) is one of the potential substitutes for antibiotics in aquatic animal feeds. Recently, the use of dietary MDPs in the aquaculture animals has been focused with much interest. In aquaculture, MDPs are used as prebiotic substance which is mostly accepted as a nutritional component for improving the growth performance and health conditions. Hence, present review is a comprehensive and an updated collection of available research reports on different MDPs (alginate, fucoidan, carrageenan, laminarin, ulvan, galactan, agar, chitin and chitosan), route of administration, dosage and applications for improving aqua feeds with emphasis on its effects on growth, biochemical indices, immune response, gut microbiota and disease resistance of aquaculture animals. This review describes the sustainability of global aquaculture production by providing a best alternative to harmful antibiotics, thereby meeting the emerging consumer demand for antibiotic-free aquatic food products.

1. Introduction

Aquaculture has emerged one of the most promising and fastest developing industries, and gives high-quality animal protein with overall world production increasing to 6.663 crore tonnes in 2012 from 6.36 crore tonnes in 2011 [1]. Along with the increasing demand for aquatic animals, the challenges faced by farmers are to obtain an increase in growth rate and reducing the disease outbreaks. There was an alteration in aquaculture practices, shifting from extensive culture towards the intensive culture. Diseases occurred more frequently because expanded the intensive aquaculture practice [2]. The use of antibiotics and chemotherapies for controlling diseases have been widely criticized due to it is expansive and spreading of drug-resistant pathogens, suppression of immune system, environmental pollution and accumulation of chemicals in aquatic animal tissues, which can be possibly dangerous to public health [3,4]. Alternatively, natural immunostimulants such as probiotics, prebiotics, synbiotics, complex carbohydrates, nutritional factors, herbs, hormones and cytokines are generally being suggested to use in aqua feeds to effectively promote growth, immune response and control various diseases in aquatic animals [5,6].

Marine environment has rich sources of natural products, such as polysaccharides, oligosaccharides, peptides, vitamins, minerals, fatty acids, sterols, carotenoids and phenolic compounds. Recent years, the great attention has been generated on MDPs isolated from marine macroalgae, microalgae, marine fungi, shellfish and corals which has broad spectrum of biological activities [7–9] (Fig. 1). Polysaccharides are prebiotic substance which can improve the growth, immune response and disease resistance of aquatic animals [10,11]. Prebiotics are indigestible dietary substances that are utilized by specific gut microbiota, which has a positive effect on the nutrition and health status of the host [12]. More

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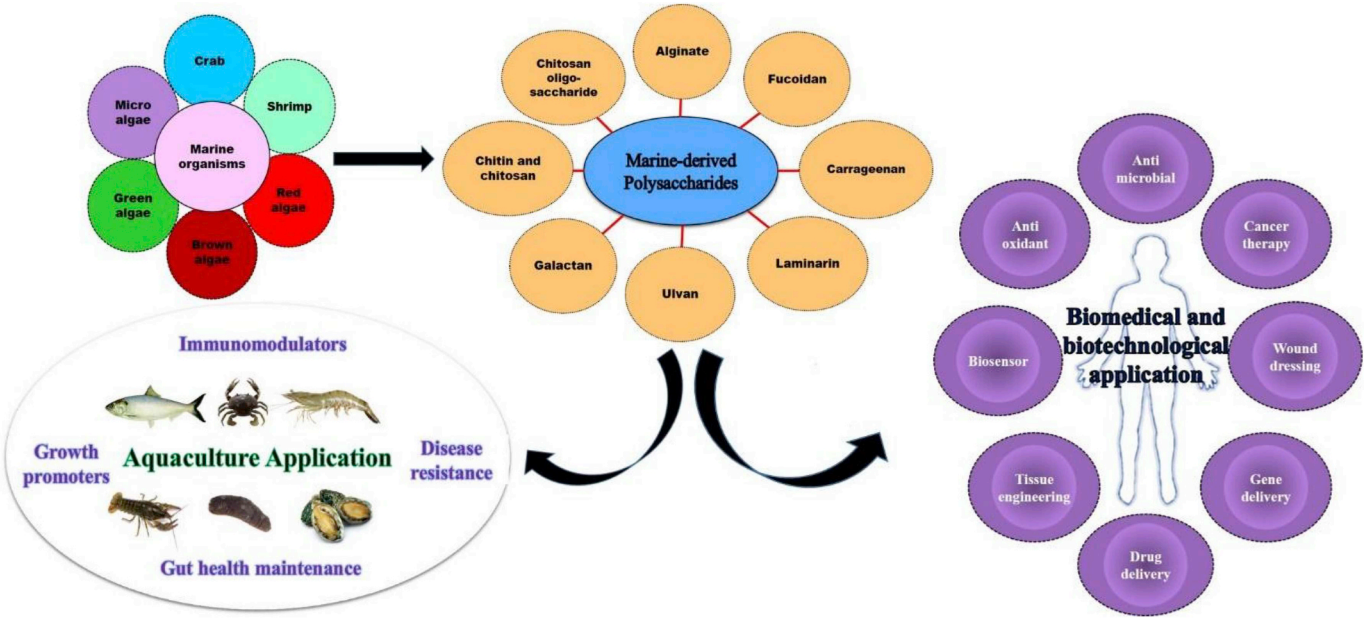

Fig. 1. Various types of marine-derive polysaccharides and their biomedical, biotechnological and aquaculture application.

recently, an impressive amount of knowledge has been published on fungal polysaccharides in fish and shrimp aquaculture and their effect on immune system [11,13]. The use of MDPs (alginate, fucoidan, carrageenan, laminarin, ulvan, galactan, agar, chitin and chitosan) has been reported in various animals (fish, crab, lobster, shrimp, sea cucumber, sea snail etc.) from Asian countries [14–18].

In this review, 161 scientific publications available in literature since 1984 to 2018 regarding the supplementation of MDPs in aquatic animals were studied. In particular, 88 and 10% of reports have been published during the year 2004–2018 and 1994–2003 respectively, and relatively few reports were published before 1994 (Fig. 2). The majority of these studies was carried out in Asia (76.1%) [countries with the highest percentages of documents are China (24.6%), India (30.2%), Taiwan (9.2%), Thailand and Iran (7.4%), Philippines (4.3%), Japan (3.7%), South Korea (3.0%), Indonesia (1.8%), and Vietnam, Turkey and Iraq (0.6%)]; Europe (12.7%) [Norway (6.7%), Spain (2.4%), UK (1.8%), France (1.2%) and Italy (0.6%)]; North America (4.2%)

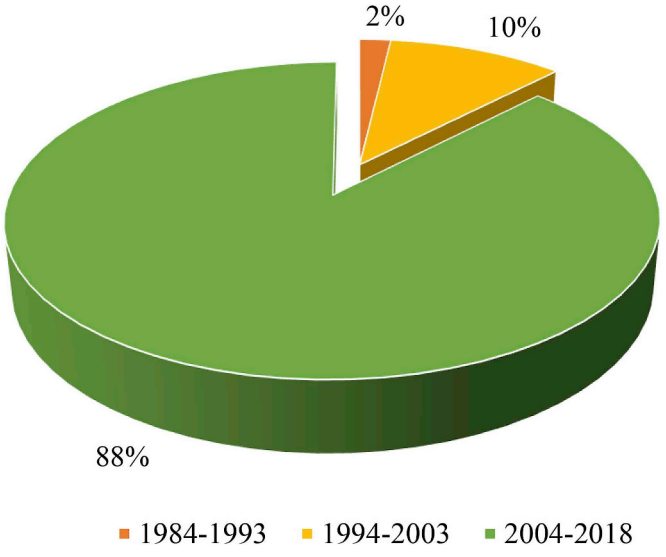

Fig. 2. Distribution between the years 1984–2018 of the literature concerning of the use of marine-derived polysaccharides in aquatic animals. Total reference publication = 161.

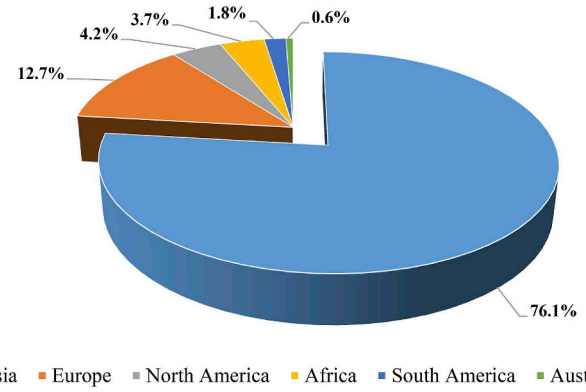

Fig. 3. Continental distribution between the years 1984–2018 of the literature concerning of the use of marine-derived polysaccharides in aquatic animals. Total reference publication = 161.

[Mexico (1.8%), Canada (1.2%) and USA (1.2%)]; Africa [Egypt (3.7%)], South America [Brazil (1.8%)], and few studies in Australia (0.6%) (Fig. 3). The purpose of this review article is to summarize and discuss the results of these studies to provide useful information for the uses of MDPs in aquaculture. This is the first detailed review on the effects of MDPs on aquatic animal's survival, growth, biochemical, haematological profile, immunological parameters and disease resistance are completely described.

2. Marine-derived polysaccharides currently under investigation

A multitude of marine organisms, such as shellfish (shrimp, crab, squilla, lobster, and crayfish etc.), marine macro algae (seaweeds), marine fungi, microalgae and corals have been identified as an efficient sources of polysaccharides and its broad spectrum of growth promotion, antioxidant, immunostimulant, antimicrobial, antitumor, anti-inflammatory, anti-stress and anticoagulant activities [7–9,19–24].

Currently, different types of MDPs have been studied in China, India, Taiwan, Thailand, Iran and South Korea for the improvement of health and disease management in aquaculture. The most studied MDPs are chitin and its derivatives (45%) extracted from shrimp, crab, lobster, krill and squid etc., alginate (23.2%) extracted from brown algae

(Phaeophyceae) including *Laminaria hyperborea*, *Laminaria digitata*, *Laminaria japonica*, *Ascophyllum nodosum* and *Macrocystis prrifere*, fucoidan (14%) mainly found in brown algae (Phaeophyceae), such as *Cladosiphon okamuranus*, *Saccharina japonica*, *Fucus vesiculosus*, *Undaria pinnatifida*, *Sargassum fusiforme*), ulvan (4.7%) obtained from green algae (Chlorophyta), such as *Ulva clathrata*, *Ulva rigida*, *Ulva prolifera, Ulva intestinalis* and *Acrosiphonia orientalis*, carrageenan (4.3%) isolated from red algae (Rhodophyta) like as *Chondrus crispus*, *Kappaphycus alvarezii* and *Eucheuma cottonii*, laminarin (4.2%) mainly found in brown algae (Phaeophyceae), like *Laminaria digitata*, galactan (3%) isolated from red algae (Rhodophyta), such as *Botryocladia occidentalis* and *Gracilaria fisheri*, agar (1.2%) isolated from red seaweed genera of *Gelidium* and *Gracilaria*, and seagrass (0.6%) polysaccharides (*Halophila ovalis*).

3. Marine-derived polysaccharides and their physicochemical properties

Over the past decades, a large numbers of natural polysaccharide has been reported that they having interesting properties that might render them suitable for use in many different areas. Among those, polysaccharides of marine origin (alginate, fucoidan, carrageenan, laminarin, ulvan, galactan, agar, chitin and chitosan) have been extensively studied and proposed for a wide range of applications. The physicochemical characterization of MDPs is shown in Table 1. MDPs are generally a kind of homo and hetropolysaccharides, consisting of fucose, galactose, glucose, glucuronic acid, mannose, mannuronic acid, rhamnose and xylose. The origin of raw materials and the extraction products have a great influence their monosaccharide composition. MDPs, such as carrageenan and galactan from red algae, alginate, fucoidan and laminarin from brown algae, ulvan from green algae are mainly composed of fucose, galactose, glucose, glucuronic acid, mannose, mannuronic acid, rhamnose and xylose [25–29]. The molecular weight of MDPs ranged from 6.2 to 5052 kDa [29–33].

Several studies have been investigated the structure of MDPs including carrageenan (β-(1,3)-Gal and α-1,4-Gal), galactan (1,4-linked-3,6-anhydro-D-Gal), alginate (β-D-Mannuronic acid and α-L-Guluronic acid), fucoidan (α-(1 → 3)-and-(1 → 4)-L-Fuc), laminarin (β-1,3-Glc, β-1,6-Glc), ulvan ((1 → 4)-β-Xyl-(1 → 4)-α-Rha) and chitin and chitosan ((β-1,4-poly-N-acetyl-D-Glucosamine) [26–28,34–39]. In recent years, many researchers have been investigated the effect of MDPs on biological activities, such as antioxidant [25–27,31,32,38,40], anti-inflammatory [41], anti-tumor [31,33,42,43], anti-microbial [32,44], anti-viral [29,36], and anticoagulant [25,28] activities.

4. Fish, shrimp and other aquatic species under investigation

Influence of MDPs on various fish species have been investigated in aquaculture. In fact, 25% of research studies have been conducted in Cyprinidae (*Carassius carassius*, *Catla catla*, *Ctenopharyngodon idella*, *Labeo rohito*, *Carassius auratus, Megalobrama terminalis* and *Cirrhinus mrigala*), 14% in Cichlidae (*Oreochromis niloticus* and *Oreochromis aureus*), 10% in Serranidae (*Epinephelus coioides*, *Epinephelus fucoguttatus* and *Epinephelus bruneus*), 4% in Gadidae (*Gadus morhua*), 3% in Acipenseridae (White sturgeon-*Acipenser transmontanus*), 3% in Moronidae (*Dicentrarchus labrax*), Latidae (*Lates calcarifer*), 3% in Scophthalmidae (*Scophthalmus maximus*), Pangasiidae (*Pangasius bocourti* and *Pangasianodon hypophthalmus*), 3% in Sparidae (*Sparus aurata*), 2% in Pleuronectidae (*Hippoglossus hippoglossus* and 2% in Clariidae (*Clarias gariepinus*). The 1% studies dealt with other fish families, such as Labridae (*Symphodus ocellatus*), Bagridae (*Pelteobagrus fulvidraco*), Mugilidae (*Mugil cephalus*), Carcharhinidae (*Fugu obscurus*), Paralichthyidae (*Paralichthys olivaceus*), Rachycentridae (*Rachycentron canadum*), Scombridae (*Rastrelliger kanagurta*), Cobitidae (*Misgurnus anguillicaudatus*), Carangidae (*Trachinotus ovatus*) and Centrarchidae (*Micropterus salmoides*). Among fish families, Salmonidae (*Oncorhynchus mykiss*, *Salmo salar* and *Salvelinus fontinalis*) have been the most investigates ones with 14% of references. In shrimp species, 85.7% of research works have been conducted in Penaeidae (*Litopenaeus vannamei*, *Penaeus monodon*, *Fenneropenaeus chinensis* and *Marsupenaeus japonicus*) and 14.3% in Palaemonidae (*Macrobrachium rosenbergii*, *Macrobrachium tenellum* and *Macrobrachium lanchesteri*). In context, 53.8% of work has been studied in Stichopodidae (*Apostichopus japonicus*), 23% in Cambaridae (*Procambarus clarkii*), 7.7% in Potunidae (*Carcinus maenas*), 7.7% in Astacidae (*Astacus leptodactylus*) and 7.7% in Haliotidae (*Haliotis diversicolor*).

5. Route of administration and dosage

MDPs have been applied almost exclusively via oral administration as an immunostimulants and less frequently via injection or immersion for the pathogen protection purpose (Fig. 4). Oral administration is the least effective route for immunostimulants as the product is slowly absorbed by the aquatic animals led to prolonged immune response, hence, it has been considered as the most appropriate method for most of the aquatic animals like fish and shrimp [45]. Also, oral administration has been considered as stress-less for aquatic animals and permits a maximum number of subjects to treated with the low cost and effort [6]. Different studies have been used for oral administration of MDPs in aquatic animals (Tables 1–3). The frequently used MDPs have been included as ingredients of dietary supplements at doses ranging from 0.1 to 50 g kg^{-1} diet and feeding experiments conducted on aquatic animals for the periods ranging from 1 to 50 days [17,46–75] [76–95]. Also, number of studies has been reported that incorporation of MDPs in the diet of aquatic animals for a longer time of duration (above 50 days) produced better results [14,71,96–110] [111–134]. Apart from above reports, some reports are available on supplementation of MDPs at smaller concentrations (0.001–0.05 g kg^{-1} diet) in the diets of aquatic animals, such as *S. salar*, *E. coioides*, *M. cephalus*, *C. carpio*, *P. monodon*, *L. vannamei*, *M. rosenbergii*, *A. japonicus* and *P. clarkia* [18,68,135–161]. While, the higher doses (above 50 g kg^{-1} diet) of MDPs have also been studied in aquatic animals, such as *C. maenas*, *P. monodon*, *M. rosenbergii*, *A. japonicus* and *A. leptodactylus* [162–167].

The minimum doses of MDPs (0.00025–10 g kg^{-1} of body weight) have been reported in aquatic animals in the mode of intraperitoneal and intravenous injection [59,81,140,168–180] (Tables 1–3). Intraperitoneal injection has been proved as one of the most effective way of administration because it enables the immunostimulant which quickly absorbed and become instant functional in organisms [45], however, it has been considered as stressful, labour intensive, relatively time consuming and becomes impractical when the animals weight is less than 10–15 g [6]. Intravenous injections are also showed both difficult and impractical when dealing with largest fishes [181].

The administration of MDPs to aquatic animals by immersion has been tested for the treatment of diseases as alternative to traditional drugs and the protocols adopted included single or frequent treatments [51,122,182–186] (Tables 1 and 2). Dipping treatment is logistically more practical for a large number of small fishes (< 5 g), however, dilution, exposure time and level of efficiency are usually not well defined for the majority of immunostimulants [6].

6. Effects on growth performance and survival

In aquaculture practices, numerous growth promoting feed additives which includes probiotics, prebiotics, synbiotics, yeast, amino acids, antioxidants, enzymes, minerals, vitamins, hormones, plant extracts and polysaccharides from different origin have been included in the diets of cultivable animals to enhance the nutrient utilization, growth performance and survival [187]. The positive effects of MDPs supplementation in aqua feeds are well documented (Tables 1–3). Many studies have been evaluated the effects of MDPs on fish, shrimp and other aquatic animals on growth indices parameters, such as weight gain (WG) [16,85,89,91,110,123,128,151,157,159,161,165,166,188–190], final

Table 1
Marine-derived polysaccharides and their physicochemical properties.

Source	Polysaccharide type	Molecular weight (kDa)	Monosaccharide composition	Backbone	Biological activities	Reference
Red algae						
Furcellaria lumbricalis	Sulphated galactan	290	ND	3,6-anhydro-D-Gal	ND	[30]
Furcellaria lumbricalis	Sulphated galactan	428	Gal 58.1	1,4-linked-3,6-anhydro-D-Gal	ND	[35]
Hypnea musciformis	Sulphated galactan	147–155	Gal	3,6-anhydro-D-Gal	Antioxidant Antitumor	[31]
Kappaphycus alvarezii	Carrageenan	390	Gal	β-(1,3)-Gal and α-1,4-Gal	Antiviral	[36]
Mastocarpus stellatus	Carrageenan	1248	Gal:Glc:Xyl:Man 87.5:5.4:4.4:2.4	β-(1,3)-Gal and α-1,4-Gal	Antioxidant Anticoagulant	[25]
Gracilaria fisheri	Sulphated galactan	ND	Gal	β-(1,3)-Gal and α-1,4-Gal	Antioxidant	[38]
Brown algae						
Macrocystis pyrifera	Alginate	297	ND	(1 → 4)-D-Mannuronic acid and (1 → 4)-L-Guluronic acid	ND	[34]
Sargassum fusiforme	Laminarin	27.6	Glc:Gal = 1.13:0.38	β-1,3-Glc, β-1,6-Glc	ND	[37]
Cystoseira barbata	Alginate	204	ManA:GulA 37:63	β-D-Mannuronic acid and α-L-Guluronic acid	Antioxidant Rheolgical Emulsifying	[26]
Cystoseira compressa	Fucoidan	545	Fuc and Uronic acid	α-1,3 or α-1,4-Fuc	Anti-inflammatory	[41]
Ascophyllum nodosum	Fucoidan	40.23	Fuc:Rha:Gal:Glc:Xyl:Man:GluA 42.5:0.00:1.12:5.5:16.7:10.5:23.7	α-(1 → 3)-and-(1 → 4)-L-Fuc	Antioxidant	[27]
Laminaria hyperborea	Laminarin	3242–5052	ND	(1,3)-β-D-glucopyranose	Antioxidant Antimicrobial	[32]
Saccharina cichorioides	Fucoidan	30	Fuc, trace in Gal	α-L-Fuc*p*	Anticancer	[43]
Green algae						
Capsosiphon fulvescens	Ulvan	ND	Rha:Xyl:Man = 45.0:44.1:10.2	(1 → 4)-β-Xyl-(1 → 4)-α-Rha	Anticoagulant	[28]
Ulva armoricana	Ulvan	140–500	Rha:Gal:Glc:Xyl 40.0:6.7:26.2:4.4	ND	Antiviral Antioxidant	[29]
Shrimp and Crab						
Crangon crangon *Scylla serrata* *Penaeus monodon*	Chitin and Chitosan	6.273, 6.267, 12 and 338	ND	(β-1,4-poly-N-acetyl-D-Glucosamine	Anticancer Antioxidant	[42] [40] [33] [39]
Litopenaeus vannamei	Chitosan	28	ND	ND	Antibacterial	[44]

Fuc: fucose, **Gal:** galactose, **Glc:** glucose, **GulA:** Glucuronic acid, **Man:** mannose, **ManA:** Mannuronic acid, **Rha:** rhamnose, **Xyl:** xylose, **kDa:** kilo Dalton, **ND:** not detected.

length (FL) and length gain (LG) [101,105,111,125,166], specific growth rate (SGR) [74,114,117,120,128,132,144,160], feed conversion ratio (FCR) [16,56,71,115,124,161,166], protein efficiency ratio (PER) [91,126,143], feed efficiency ratio (FER) [56,71,157,166,191], feed intake (FI) [154,160], and survival (SUR) [52,57,73,76,85,92,93,95,158,176,192].

Several MDPs have been proved to be considering as growth promoters in numerous aquatic species. Sodium alginate and fucoidan incorporated feed fed *O. niloticus* showed significant improvement in WG, SGR and FCR have been reported [16,89]. Nazir et al. [128] observed that the increased WG, SGR, FCR and PER in *L. rohita* fed on diet supplemented with fucoidan. Oral administration of laminarin and ulvan produced significant elevations in FI, WG, SGR, PER and FER in *E. coioides* and *M. cephalus* has also been reported [74,160]. Moreover, the elevated level of LG, WG, SUR, SGR and FCR have been reported in *S. salar*, *D. labrax*, *P. clarkia, C. maenas, A. leptodactylus, A. japonicus* and *H. diversicolor* when fed with dietary MDPs, such as chitin and chitosan [69,81,85,86,125,146,158,164,166]. Further, dietary administration of MDPs, such as alginate, fucoidan, chitin and crude polysaccharides from seagrass shown better results on LG, SUR, WG and FCR in crustaceans, such as *L. vannamei*, *P. monodon* and *M. rosenbergii* have also been reported [92,93,95,157].

7. Effects on feed utilization

Diet supplemented with polysaccharides are digested and absorbed more efficiently due to the ability of polysaccharides to stimulate the secretion of digestive enzymes (amylase, protease and lipase etc.) which turn to better utilization and digestion of nutrients, followed by improved health condition and growth of aquatic animals [11,193]. Very few studies have investigated that the effects of MDPs on the activities of digestive enzyme in aquatic animals (Table 1). Yan et al. [90], Hua et al. [101] and Gawlicka et al. [194] reported that dietary supplementation of MDPs, such as with chitosan and carrageenan have ability to influence on the digestive enzymes activities (amylase, amino protease and lipoprotein lipase) in *F. obscurus, A. transmontanus* and *M. anguillicaudatus*.

8. Effects on haematological indices

The haematological indices parameters includes red blood cell count (RBC), white blood cell count (WBC), haematocrit (HCT), haemoglobin (Hb) and erythrocyte indices (mean cell volume (MCV), mean cell haemoglobin (MCH) and mean cell haemoglobin concentration (MCHC) play a significant role to evaluate the physiological condition of aquatic animals. The age, fish species, sexual maturity cycle and

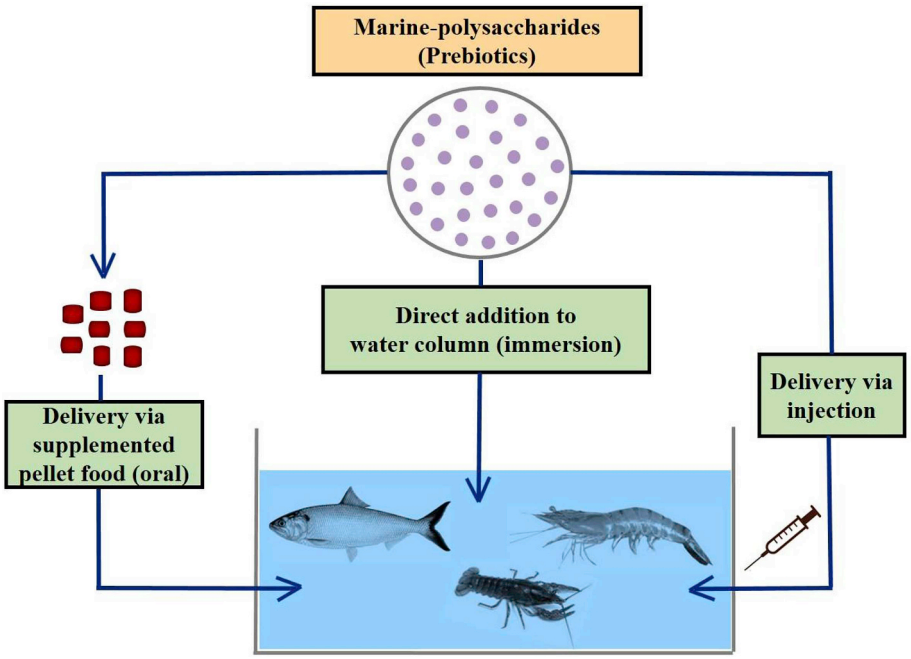

Fig. 4. Different routes of marine polysaccharides administration in aquatic animals.

health status are alteration factor of haematological parameters [195]. Haematological indices show the oxygen carrying ability in fish [196]. The amount of oxygen received by tissues depends on the maturation of the erythrocytes. Hence, these indices can be useful in determination of changes in animal's health when administration of immunostimulants [187]. Many researchers have been observed the positive effects of MDPs on the haematological parameters (stimulation of erythrocytes and leucocytes) in fishes, shrimps and other aquatic animals (Tables 1–3). Faghani et al. [56,199] and Akbari et al. [124] reported that the dietary supplementation of alginate enhanced the RBC, WBC, Hb and erythrocyte indices (MCV, MCH and MCHC) leads to enhancement of fish health and immune status. Diets supplementation of alginate, ulvan and chitin showed significantly increased lymphocytes (LYM), monocytes (MON), Hb, RBC, WBC, HCT and erythrocyte indices in *H. huso*, *O. niloticus* and *E. bruneus* have been reported [61,62,105,130]. Further, dietary supplementation of chitin in *C. mrigala* induced significant increases in RBC and WBC indices [75]. Significantly higher RBC and WBC counts were observed in *C. mrigala* [75], *L. rohita* [117], *L. calcarifer* [113], *T. ovatus* [115] and *R. kanagurta* [126] fed with dietary chitin and chitosan. In contrast, *C. carpio* fed with dietary chitosan had showed decreases in RBC and WBC counts [197].

In crustaceans, *L. vannamei* fed diet containing alginate [14,48,92,93,161], fucoidan [87,149], carrageenan [122,142] and chitin [171] showed significantly higher total haemocyte count (THC) and differential haemocyte count (DHC). *P. monodon* fed with fucoidan [123,198], ulvan [123,198], galactan [152] and seagrass crude polysaccharides [95] diets produced significantly better THC and DHC. In context, *P. monodon* fed with dietary chitin showed decreased THC has been reported [190]. Fucoidan and laminarin incorporated diets produced significant elevations in THC in the shrimp *F. chinensis* has also been reported [50,173]. Fucoidan diets produced significantly higher THC in the shrimps *M. japonicus* and *M. rosenbergii* have been observed by Traifalgar et al. [144] and Arizo et al. [157]. The significant improvements in THC has been reported in the *C. maenas* and *P. clarkia* fed with chitin and chitosan supplementation diets [146,158,164].

9. Effects on biochemical indices

Serum/plasma proteins including albumin (ALU) play a crucial role in osmotic pressure maintaining of blood which lead to proper transportation of different components [201]. Serum globulins (GLOB) like gamma globulins are the source of immunoglobulins which imitates antibodies concentration and the immune status of fish [187]. The influence of MDPs on biochemical components of aquatic animals have been reported by earlier studies [61,62,74,75,78,91,95,101,113,124,155,176,177,185]. Fishes, such as *O. niloticus*, *E. bruneus, C. mrigala, L. calcarifer, O. mykiss, C. catla, C. carpio* and crustaceans, such as *F. obscurus* and *P. monodon* fed diets supplemented with MDPs (alginate, chitin, chitosan and seagrass crude polysaccharides showed significant increases in serum total protein (TP), ALU and GLOB has been observed by earlier studies [58,61,62,75,78,95,101,113,124,185] (Tables 1–3). Whereas, Campos et al. [176] reported that the decreased TP in *P. monodon* fed diet containing seagrass crude polysaccharides. Furthermore, the insignificant alterations in TP, ALU and GLOB have also been reported in *O. niloticus, E. coioides* and *C. carpio* fed on dietary MDPs, such as ulvan [130], chitooligosaccharide [91], fucoidan [177] laminarin [74] and chitosan [155].

Blood glucose (GLU) level determination is often used as an indicator of non-specific stress in aquatic animals [202]. Few studies have been reported that supplementation of MDPs (fucoidan, chitin and chitiooligosaccharide) in the diets of aquatic animals can significantly reduce the blood GLU level (Tables 1–3). The significantly decreases in GLU and serum cortisol (SCORT) level in *P. fulvidraco, L. rohita, O. mykiss* and *P. clarkii* fed with dietary fucoidan [128,129], chitin [119] and chitooligosaccharide [203] have been observed. However, dietary fucoidan and chitooligosaccharide showed insignificant changes in GLU level in *L. vannamei* and *O. niloticus* [91,176].

MDPs such as, fucoidan, chitooligosaccharide, chitosan and oligochitosan can stimulate lipid metabolism that catabolizes body fatty acids as a main energy expenditure which leads to efficient protein accumulation in tissues, followed by better growth performance in aquatic animals [190]. However, information about the effect of MDPs on blood lipids (LIP) is very scanty in aquatic organisms (Tables 1 and 2). Diet containing chitosan significantly increased total LIP in *L. rohita* [117]. Also, the significant elevations in triglyceride (TG) and total cholesterol (TC) have been reported in *P. monodon* fed with chitosan diet [190]. Moreover, lower plasma TG, HDL-cholesterol and LDL-cholesterol have been observed in *P. fulvidraco* and *O. niloticus* fed on fucoidan and chitooligosaccharide supplemented diets [91,129]. *L.*

Table 2
Uses of marine-derived polysaccharides on fish aquaculture.

Marine-derived polysaccharides	Fish species	Doses	Duration of experiment	Growth performance and survival[a,b]	Biochemical and haemato-immunological parameters[a,b]	Disease resistance	References
Alginate							
	Epinephelus coioides	0.01–0.03 gkg^{-1}	5 days	n.a.	ACH_{50}, SOD, LYZ, PHA, RBA (↑)	*V. alginolyticus*	[175]
	Epinephelus fuscoguttatus	5-10 gkg^{-1}	98 days	SUR, WG (↔)	LEU, RBA, PHA, PHI, ACH_{50}, LYZ (↑)	*V. alginolyticus*	[104]
	E. fuscoguttatus	1 or 2 gkg^{-1}	12 days	SUR (↑)	ACH_{50}, LYZ, RBA, PHA, SOD (↑)	*Streptococcus* sp.	[52]
	E. coioides	0.5–2 gkg^{-1}	56 days	PWG, FE (↑)	ACH_{50}, RBA, SOD, HA, PHA, LYZ (↑)	*Streptococcus* sp.	[140]
	Epinephelus bruneus	0.5–2 gkg^{-1}	28 days	n.a.	ACH_{50}, LYZ, HA, RBA, SOD, PHA (↑)	*S. iniae*	[15]
	E. fuscoguttatus	2 gkg^{-1}	9 days	n.a.	MX (↑)	n.a.	[65]
	E. coioides	1 gkg^{-1}	12 days	n.a.	ACH_{50}, LYZ, PHA, SOD, RBA (↑)	*Pho. damselae* subsp. *piscicida*	[88]
	Oreochromis niloticus	0.5–2 gkg^{-1}	14 days	MOR (↓)	TP, ALU, GLOB, LEU, PHA, PHI, LYZ (↑)	*A. hydrophila*	[58]
	O. niloticus	5 gkg^{-1}	63 days	WG, SGR, FCR, PER (↔)	BBC, GM, GMB (↔)	*A. hydrophila*	[110]
	O. niloticus	10 gkg^{-1}	60 days	SGR, FCR (↑)	LYZ, RBA, PHA, ACH_{50} (↑)	*S. agalactiae*	[120]
	O. niloticus	10-30 gkg^{-1}	60 days	SUR, SGR, FCR (↑)	LYZ, ACH_{50}, PHA, RBA (↑)	*S. agalactiae*	[121]
	O. niloticus	10 gkg^{-1}	50 days	WG, FCR, SGR, SUR (↑)	ACH_{50}, PHI, RBA, LYZ (↑)	*S. agalactiae*	[16]
	Salmo salar	50 gkg^{-1}	4 days	MOR (↓)	LYZ (↑) Hb (↓) DM, TP, HSI (↔)	n.a.	[46]
	Oncorhynchus mykiss	5 gkg^{-1}	10 days	GR, SGR, FCR, SUR (↑)	RBC, WBC, HCT, Hb, MCH, MCHC (↑)	n.a.	[56]
	O. mykiss	5 gkg^{-1}	10 days	GR, SGR, FCR, CF, SUR (↑)	RBC, HCT, MCV, Hb, MCH, MCHC, WBC (↑)	n.a.	[199]
	O. mykiss	5 gkg^{-1}	70 days	FCR, SGR, WG (↑)	RBC, WBC, NEU, IL-8, LYZ, TP (↑)	n.a.	[124]
	Gadus morhua	0.1–1 gkg^{-1}	60 days	SGR (↑) MOR (↓)	n.a.	n.a.	[127]
	G. morhua	100 μgml^{-1}	1 day	n.a.	RBA, ACP, ALP, MPO (↔) CPF (↓)	n.a.	[148]
	Huso huso	2-6 gkg^{-1}	60 days	FW, FL, FCR, SGR, CF, PWG (↑) SUR (↔)	LYM, HCT, MON, Hb, RBC, WBC, MCV, MCH, MCHC (↑)	n.a.	[105]
	H. huso	5 gkg^{-1}	90 days	WG (↑)	LYM, NEU, EOS, LYZ (↑)	n.a.	[107]
	Dicentrarchus labrax	5 gkg^{-1}	60 days	n.a.	C3, LYZ, HSP (↑)	n.a.	[100]
	Cyprinus carpio	0.01–0.04 gkg^{-1}	7 days	SUR (↑)	n.a.	*E. tarda*	[168]
	C. carpio	0.25–0.5 gkg^{-1}	7 days	SUR (↑)	ACH_{50}, PHA, RBA (↑)	*E. tarda*	[170]
	Hippoglossus hippglossus	2–30 μm	43 days	MOR (↓)	n.a.	Vibriosis	[138]
	Clarias sp.	2-6 gkg^{-1}	15 days	n.a.	NBT, PHA, PHI, LEU, HCT (↑)	n.a.	[72]
	Sciaenops ocellatus	10 gkg^{-1}	49 days	WG, FE (↓) SUR (↔)	PHA, Ig, GCP (↑) HSI, IPF (↔)	n.a.	[83]
Fucoidan							
	O. niloticus	0.04–0.06 gkg^{-1}	15 days	n.a.	PHA, TP, LEU, PHI (↔)	n.a.	[177]
	O. niloticus	5-15 gkg^{-1}	30 days	FW, RC, WG, AFC, SUR, SL, HL, BH (↑)	n.a.	n.a.	[89]
	Clarias gariepinus	4 and 6 gkg^{-1}	21 days	SUR (↑)	RBA, PHA, LYM, LYZ, NO, BCA (↑)	n.a.	[73]
	Pelteobagrus fulvidraco	0.5–2 gkg^{-1}	84 days	SUR (↑)	SOD, CAT, LYZ, PHI, RBA (↑) MDA, TG, TC, HDL-C, LDL-C, GLU (↓)	*A. hydrophila*	[129]
	Lates calcarifer	5-10 gkg^{-1}	52 days	FW, FL, SGR, FI, FCR, SUR (↑)	MFA (↑) HSI (↔)	n.a.	[111]
	C. carpio	0.1–10 gkg^{-1}	14 days	MOR (↓)	LYZ, SPO, IL-1β, LYZ (↑)	*A. hydrophila* *E. tarda*	[84]
	L. rohita	10-20 gkg^{-1}	60 days	WG, SGR, FCR, PER (↑)	RBA, MPO, LYZ, Ig, PHA, TLC (↑) A/G, GLU (↓)	*A. hydrophila*	[128]
Carrageenan							
	A. transmontanus	n.a.	16 days	SUR, BW (↑)	ALP, AP (↓)	n.a.	[194]
	C. carpio	0.01–0.015 gkg^{-1}	6 days	SUR (↑)	n.a.	n.a.	[192]
	C. carpio	0.00025 gkg^{-1}	21 days	SUR (↑)	ACH_{50}, PHA, RBA (↑)	n.a.	[169]
	O. niloticus	5-20 gkg^{-1}	28 days	WG (↑)	n.a.	n.a.	[66]
Laminarin							
	S. salar	0.01–0.02 gkg^{-1}	30 min	n.a.	Intestinal uptake (↑)	n.a.	[183]
	S. salar	0.0016 gkg^{-1}	12 days	n.a.	Blood (↑) PIM (↓)	n.a.	[178]
	S. salar	10-50 μgkg^{-1}	2 days	n.a.	PHA, O_2-, ACP, Mφ	n.a.	[135]
	S. salar	0.015 gkg^{-1}	2 days	n.a.	O_2-,ACP (↑)	n.a.	[184]

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Table 2 (*continued*)

Marine-derived polysaccharides	Fish species	Doses	Duration of experiment	Growth performance and survival[a,b]	Biochemical and haemato-immunological parameters[a,b]	Disease resistance	References
	G. morhua	0.0016 gkg^{-1}	12 days	n.a.	Spleen and kidney endocylically active cells (↑)	n.a.	[179]
	E. coioides	5-15 gkg^{-1}	48 days	FI, WG, FE (↑)	IL-1β, 1L-8, TLR2, TP, LYZ, CAT, SOD (↑) CREA, ALP, C3, C4 (↓) ALT, AST (↔)	n.a.	[74]
Ulvan							
	O. niloticus	1-10 gkg^{-1}	90 days	WG, SGR, FCR, FC (↑)	HCT, WBC, PHA (↑) Hb, RBC, TP, ALU, GLOB (↔)	n.a.	[130]
	M. cephalus	0.005–0.015 gkg^{-1}	56 days	WG, SGR, PER (↑) MOR (↓)	LYZ, PHA, RBA, SOD, GSH, MDA (↑)	*P. damselae*	[160]
	P. maxima	0.05 gkg^{-1}	1 h	n.a.	NBT, IL-1β (↑)	n.a.	[174]
Galactan							
	O. niloticus	5-20 gkg^{-1}	28 days	FW, WG (↑)	n.a.	n.a.	[47]
Agar							
	P. bocourti	1-3 gkg^{-1}	75 days	SGR, SUR (↑) FCR (↓)	LYZ (↑)	*A. hydrophila*	[71]
	P. bocourti	2 gkg^{-1}	28 days	SUR, FCR, SGR (↑)	LYZ, PHA, RBA, ACH_{50} (↑)	*A. hydrophila*	[215]
Chitin and its derivatives							
Chitin							
	S. aurata	10 gkg^{-1}	10 days	n.a.	RBA, PHA, C3, CTA (↑)	n.a.	[180]
	S. aurata	0.025–0.1 gkg^{-1}	42 days	n.a.	CTA, C3, RBA, PHA (↑) LYZ (↔)	n.a.	[136]
	S. aurata	0.001 gkg^{-1}	48 h	n.a.	PHA, CTA RBA (↔)(↑)	n.a.	[137]
	O. mykiss	0.04–0.25 gkg^{-1}	84 days	n.a.	CLE (↔)	n.a.	[96]
	O. mykiss	0.01–0.05 gkg^{-1}	35 days	n.a.	NEU, RBA (↑)	n.a.	[63]
	E. bruneus	10 gkg^{-1}	28 days	n.a.	RBC, WBC, Hb, LYM, MON, NEU, PHA, RBA, C3, APA, MGB, LYZ, TP, MPO (↑) MCV, MCH, MCHC (↔) MOR (↓)	*P. dicentrarchi*	[61]
	E. bruneus	10 gkg^{-1}	28 days	n.a.	RBC, WBC, HCT, Hb, LYM, MON, ALU, GLOB, LYZ, PHA, C3 (↑) MCV, MCH, MCHC (↓)	*V. alginolyticus*	[62]
	O. niloticus x *O. aureus*	20-100 gkg^{-1}	56 days	WG (↑) FCR (↓) SUR (↔)	LD, DM (↓)	n.a.	[98]
	S. salar	50 gkg^{-1}	n.a.	n.a.	LAB, GMB (↑)	*A. salmonicida* *V. anguillarum* *M. viscosa* *C. maltaromatium*	[17]
	C. carpio	10 gkg^{-1}	90 days	RPS, WG (↑)	LYZ, NBT, WBC (↑)	*A. hydrophila*	[102]
	C. mrigala	10 gkg^{-1}	28 days	MOR (↓)	WBC, RBC, Ht, LYM, MON, NEU, Hb, TP, ALU, GLOB, A/G, PHA, LYZ, C3 (↑)	*A. invadans*	[75]
	C. catla	5-20 gkg^{-1}	14 days	n.a.	LEU, RBA, LYZ, TP (↑)	n.a.	[78]
	S. salar *G. morhua* *H. hippoglossus*	10-50 gkg^{-1}	91 days	LG, Wt, CF, SGR (↔)	FP (↑) APD, DM, ALD (↓)	n.a.	[125]
Chitosan							
	C. carassius	3-20 gkg^{-1}	60 days	n.a.	LYZ, PHA (↑)	n.a.	[99]
	C. carpio	0.075–0.15 gkg^{-1}	4 days	n.a.	LYZ, BLA, CPN (↑)	*Ptychobothrium* sp	[185]
	C. carpio	0.035–0.037 gkg^{-1}	4 days	n.a.	TP, GST, CAT, LYZ (↑)	n.a.	[186]
	C. carassius	3-20 gkg^{-1}	60 days	WG (↑) SUR (↔)	n.a.	*A. hydrophila*	[103]
	M. terminalis	n.a.	60 days	WG (↑) FCR (↓)	CP, SER, RFN (↑) MOI, NEAA, PRO (↓)	n.a.	[188]
	C. idellus	2.5–10 $g\,kg^{-1}$	40 days	WG (↑)	CP, FCF (↑) CF (↓)	n.a.	[53]
	C. carassius	5 $g\,kg^{-1}$	n.a.	SGR (↑) FCE (↓)	n.a.	*A. hydrophila*	[220]
	C. carpio	10–50 $g\,kg^{-1}$	70 days	RPS, FCR, SGR (↑) MOR (↓)	PHA, PHI, SBA (↑)	*A. hydrophila*	[106]
	C. carassius	1–20 $g\,kg^{-1}$	30 days	n.a.	GMP (↑)	n.a.	[64]
	C. carpio	n.a.	56 days	n.a.	LYZ, PHA (↑) WBC, RBC, SOD (↓) ACP (↔)	*A. veronii*	[197]
	L. rohita	5–12.5 $g\,kg^{-1}$	90 days	SGR, FCR (↑)	RBC, WBC, Hb, SP, LIP, LYZ (↑)	*A. hydrophila*	[117]
	C. auratus	1.8–20 $g\,kg^{-1}$	75 days	SGR, FER, SUR (↓)	PHA, RBA, ACH_{50}, SOD (↑) PD, DM, MDA (↓) MPO (↔)	*A. hydrophila*	[2]

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Table 2 (*continued*)

Marine-derived polysaccharides	Fish species	Doses	Duration of experiment	Growth performance and survival[a,b]	Biochemical and haemato-immunological parameters[a,b]	Disease resistance	References
	C. carpio	0.0025–0.01 gkg^{-1}	60 days	MOR (↓)	RBA (↑) LYZ, SBA, TP, GLOB, WBC, LEU (↔)	*A. hydrophila*	[155]
	C. carpio	7.5–20 $g\,kg^{-1}$	45 days	SUR (↑)	RBA, SBA, LYZ (↑)	*A. hydrophila*	[76]
	C. carpio	1 $g\,kg^{-1}$	21 days	n.a.	MDA (↑) CAT, G6PDH, LDH, AST (↓)	n.a.	[79]
	D. labrax	2.5–10 $g\,kg^{-1}$	20 days	SUR, SGR, TL, Wt, TW, WG, ADW (↑)	n.a.	*A. hydrophila*	[85]
	S. fontinalis	100 $\mu g\,kg^{-1}$	28 days	MOR (↓)	n.a.	*A. salmonicida*	[182]
	O. mykiss	2.5–10 $g\,kg^{-1}$	56 days	MOR (↓)	GLU, WBC, LYM, NEU (↑)	*Environmental stresses*	[112]
	F. obscurus	2–10 $g\,kg^{-1}$	56 days	WG, LG (↑)	TP, AMY, RNA/DNA (↑) HSI (↓) PRO (↔)	n.a.	[101]
	P. olivaceus	10 $g\,kg^{-1}$	84 days	FBW (↑)	MPO, RBA, LYZ (↑)	n.a.	[134]
	R. canadum	3, 6 $g\,kg^{-1}$	56 days	SUR, SGR (↑)	LYZ, ACP (↑)	*V. harveyi*	[108]
	L. calcarifer	5–20 $g\,kg^{-1}$	60 days	SUR (↑)	RBC, WBC, TSP, ALU, GLOB, A/G, PHA RBA, LYZ, SBA (↑)	*V. anguillarum*	[113]
	O. niloticus	5–20 $g\,kg^{-1}$	21 days	MOR (↓)	PHA, PHI, NBT, LYZ, ACH_{50} (↑)	*A. hydrophila*	[80]
	R. kanagurta	5–10 $g\,kg^{-1}$	60 days	FW, WG, PER, CF (↑) FCR (↓)	WBC, RBC (↑) MCV, MCH (↓)	n.a.	[126]
	M. anguillicaudates	5–50 $g\,kg^{-1}$	50 days	WG (↑)	LYZ, SOD, CAT, GTP, GMB (↑) LPL, FABP (↓)	n.a.	[90]
Chitooligo-saccharides							
	O. mykiss	0.02–0.06 $g\,kg^{-1}$	56 days	SUR (↑)	PHA, RBA (↑) SCORT(↓) BBC (↔)	*A. hydrophila*	[203]
	S. maximus	0.125–0.25 $g\,kg^{-1}$	50 days	SUR (↑)	n.a.	n.a.	[60]
	S. maximus	0.075–1.2 $g\,kg^{-1}$	56 days	SGR (↑) FCR, MOR (↓)	PHA, SOD (↑) MDA, MT (↔)	*E. tarda*	[114]
	T. ovatus	2–6 $g\,kg^{-1}$	56 days	FW, SGR (↑) FCR, MOR (↓)	WBC, RBC, LYZ, SOD (↑)	*V. harveyi*	[115]
	C. carpio	2 $g\,kg^{-1}$	56 days	FW, SGR (↑)	WBC, RBA, PHA, LYZ, SOD (↑)	*A. veronii*	[116]
	O. niloticus x *O. aureus*	8–24 $g\,kg^{-1}$	35 days	MOR (↓) WG, FCR, SUR (↔)	TNFα, HSP70 (↓)	*A. hydrophila*	[77]
	O. niloticus	0.1–0.8 $g\,kg^{-1}$	50 days	WG, SGR, FER, PER (↑)	TP, PHA, SBA, LYZ (↑) TG, TC (↓) ALU, GLOB, GLU (↔)	n.a.	[91]
	P. hypophthalmus	0.05–0.2 $g\,kg^{-1}$	45 days	WG, SGR (↑) MOR (↓)	PHA, LYZ (↑)	*E. ictaluri*	[159]
	M. salmoides	2 $g\,kg^{-1}$	56 days	FW, SGR (↑) FCR, MOR (↓)	RBA, PHA, LYZ, SOD, WBC, NO, iINOS (↑)	*A. hydrophila*	[131]
Chitosan nanoparticles							
	L. calcarifer	0.2 $g\,kg^{-1}$	n.a.	SUR (↑) MOR (↓)	n.a.	*V. anguillarum*	[191]
	O. niloticus	5 $g\,kg^{-1}$	60 days	FW, DWG, FCR (↑)	IA (↑)	n.a.	[109]
	O. mykiss	0.15 $g\,kg^{-1}$	20 days	n.a.	LYZ, C3 (↑)	n.a.	[67]
	D. labrax	10–200 $g\,kg^{-1}$	42 days	SUR (↑)	n.a.	*V. anguillarum*	[86]

n.a-not available.

[a] **A/G**: albumin/globulin ratio, **ACP**: acid phosphatase, **ACH_{50}:** Alternative complement pathway: **ADW**: Average daily weight, **AFC**: apparent food conversion, **ALD**: apparent lipid digestibility, **ALP**: alkaline phosphate, **ALT:** Alanine aminotransferase, **ALU**: albumin, **AMY**: amylase, **AP**: amino peptidase, **APA**: antiprotease activity, **APD**: apparent protein digestibility, **AST**: alanine aminotransferases, **BBC**: body biochemical compoPROsition, **BCA**: bactericidal activity, **BLA**: bacteriolytic activity, **BW**: body weight, **C3**: complement 3, **C4**: complement 4, **CAT**: catalase, **CF**: condition factor, **CF**: crude fat, **CLE**: chitinolytic enzymes, **CP**: crude protein, **CPF**: cellular proliferation, **CPN**: ceruloplasmin, **CREA**: creatinine, **CTA**: cytotoxic activity, **DM**: dry matter, **DM**: dry matter digestibility, **DWG**: daily weight gain, **EOS**: eosinophil, **$FABP_2$**: fatty acid binding protein 2, **FBW**: Final body weight, **FC**: feed consumption, **FCF**: feeding coefficient, **FCR**: feed conversion ratio, **FE**: feed efficiency, **FER**: feed efficiency ratio, **FI**: feed intake, **FL**: final length, **FP**: faecal protein, **FW**: final weight, **G6PDH**: glucose-6-phosphate dehydrogenase, **GCP**: goblet cell proliferation, **GLOB**: globulin, **GLU**: glucose, **GM**: gut microbes, **GMB**: gastrointestinal microbial balance, **GMB**: gut micro biota, **GMP**: gut microbial population, **GR**: growth rate, **GSH**: glutathione, **GST**: glutathione s-transferase, **HA**: haemagglutination activity, **Hb**: haemoglobin, **HCT**: haematocrit, **HDL-C**: higher density lipoprotein-cholesterol, **HIS**: hepatosomatic index, **HL**: head length, **HSP**: heat shock protein, **IA**: inosinic acid, **I_g**: immunoglobulin, **IL-1β**: interleukin 1 beta, **IL-8**: interleukin −8, **iNOS**: inducible nitric acid synthase activity, **IPF**: idiopathic pulmonary fibrosis, **LAB**: lactic acid bacteria, **LD**: lipid digestibility, **LDH**: lactate dehydrogenase, **LDL-C**: low density lipoprotein-cholesterol, **LEU**: Leucocytes, **LG**: length gain, **LIP**: lipid, **LPL**: lipoprotein lipase, **LYM**: lymphocytes, **LYZ**: lysozyme activity, **MCH**: mean cell haemoglobin, **MCHC**: mean cell haemoglobin concentration, **MCV**: mean cell volume, **MDA**: malondialdehyde activity, **MFA**: muscle fibre area, **MGB**: α_2 macroglobulin, **MOI**: moisture, **MON**: monocyte, **MOR**: mortality, **MPO**: myeloperoxidase, **MT**: hepatic metallothionein, **M_x**: M_x gene, **Mφ**: macrophages, **NBT**: nitro blue tetrazolium, **NEAA**: non-essential amino acid, **NEU**: neutrophil, **NO**: nitric oxide activity, **O_2^-**: superoxide anion production, **PER**: protein efficiency ratio, **PHA**: phagocytic activity, **PHI**: phagocytic index, **PRO**: proline, **PWG**: percentage weight gain, **RBA**: respiratory burst activity, **RBC**: red blood cells, **RC**: average ratio consumption, **RFN**: relative fatness, **RNA/DNA**: RNA/DNA ratio, **RPS**: relative percent survival, **SBA**: serum bactericidal activity, **SCORT**: serum cortisol level, **SER**: serine, **SGR**: specific growth rate, **SL**: standard length, **SOD**: superoxide dismutase, **SP**: serum protein, **SPO**: serum peroxide, **SUR**: survival, **TC**: total cholesterol, **TG**: triglyceride, **TL**: total length, **TLC**: total leucocyte count, **TLR2**: toll like receptors, **TNFα**: tumor necrosis factor alpha, **TP**: total protein, **TW**: total weight, **WBC**: white blood cells, **WG**: weight gain, **Wt**: Weight.

[b] Variation in experimental fish compared to controls: (↑) significant increase; (↓) significant decrease; (↔) no significant changes.

vannamei fed a diet containing oligochitosan had showed insignificant changes in TC and LDL-cholesterol has also been reported [141].

Alkaline phosphatase (ALP) and acid phosphatase (ACP) are considered as important regulative enzymes in animals metabolic process. These enzymes plays a significant role in digestion, absorption, and transition of nutrients [204]. An increase in serum ALP activity indicates higher breakdown of the energy reserves which are used for the growth and survival of fish [205]. Alanine aminotransferase (ALT) and aspartate aminotransferase (AST) are ubiquitous aminotransferases that represent indices for the diagnosis of tissue and hepatopancreatic injury in animals [206]. A range of reports suggests that supplementations of MDPs in aquatic animals can modulate these enzymes activities (Tables 2–4). The significant elevations in ACP and ALP activities have been reported in *A. japonicus* fed diets with fucoidan [55], carrageenan [59], alginate [18], ulvan [81] and chitooligosaccharide [133]. Also, the significant elevation in ALP activity has also been noted in *P. clarkii* fed with chitosan diet [119]. In contrast, the decreased ALP activity has been reported *A. transmontanus* [194] and *E. coioides* [74] fed with carrageenan and laminarin incorporated diets. The significant alterations in ACP and ALP activities have also been observed in *G. morhua* fed an alginate supplementation diet [148]. Niu et al. [118] reported that higher ALT and AST activates in *P. monodon* fed diet with chitosan. However, dietary inclusion of laminarin showed insignificant changes in ALT and AST activates in *E. coioides* [74].

10. Effects on antioxidant enzymes activity

Superoxide dismutase (SOD) and catalase (CAT) involves in cellular defences against uncontrolled oxidative processes and catalyze the dismutation of superoxide radical and hydrogen peroxide [207]. These two enzymatic antioxidants are considered as the first line of defence against oxygen toxicity due to their inhibitory effects on oxygen radical formation [208,209]. An increase in the activity of the SOD enzyme probably neutralises the impact of increased reactive oxygen species (ROS) generation [210]. Effects of MDPs such as, alginate, chitosan, chitooligosaccharide, chitin, carrageenan, galactan and ulvan on antioxidants activities of aquatic animals have been studied by several researchers [52,93,114,131,160,186]. CAT is widely distributed in biological tissue and rapidly catalyzes the decomposition of hydrogen peroxide into oxygen and water [211]. The significant elevations in SOD activity has been reported in *E. coioides* [88,140,175], *E. fuscoguttatus* [52], *E. bruneus* [15], *L. vannamei* [172], *P. monodon* [14,93] and *H. diversicolor* [69] when fed on alginate supplemented diet. Similarly, the oral administration of fucoidan showed enhanced SOD and CAT activity has been reported in *P. fulvidraco* [129], *E. coioides* [74], *M. cephalus* [160], *L. vannamei* [54,87], *P. monodon* [123,198] and *A. japonicus* [55]. Also alterations in SOD and CAT activities in fishes (*A. japonicas, C. auratus*, *M. anguillicaudate, S. maximus*, *T. ovatus*, *C. carpio* and *M. salmoides*) and crustaceans (*P. monodon*, *L. vannamei* and *P. clarkia*) fed diets with chitosan, chitooligosaccharide, chitin, carrageenan, galactan, ulvan have been reported by earlier studies [2,59,79,81,90,114–116,119,131,152,186,197]. Whereas, the insignificant changes in SOD activity has been observed in *F. chinensis* fed with fucoidan supplemented diet [50].

11. Effects on immune response

The immunomodulatory effects of MDPs have been well reported in various fishes, crustaceans and other aquatic animals. Immunostimulants, such as polysaccharides possibly connect with specific receptors on surface of cells leads to stimulate the expression of intracellular genes which encoding for antimicrobial molecules [212]. The research findings also exhibit significant effects of MDPs on immune response of various aquatic animals [46,50,76,92,107,124,159].

11.1. Non-specific immune response

MDPs can improve various components of the innate immunity, such as serum lysozyme, alternative complement pathway, anti-protease activities, phagocytic activity, respiratory burst and phenoloxidase enzyme activities in aquatic animals (Tables 2–4). Lysozyme (LYZ) is a bacteriolytic enzyme that occurs in mucus, lymphoid tissue, and plasma and involved in a wide range of protective mechanisms, such as bacteriolysis, complement-mediated opsonisation and antibacterial activities [213]. The LYZ activity have been reported to enhanced in *C. carpio* fed diets with fucoidan [84], chitin [102], chitosan [76,185,197], and chitooligosaccharide [116]. A similar immunostimulatory effects were observed in various grouper species (*E. bruneus*, *E. fuscoguttatus* and *E. coioides*) fed diets supplemented with alginate [15,52,88,104,140,175], laminarin [74], and chitin [61,62], *O. niloticus* fed a diet with alginate [12,16,58,120], chitosan [80] and chitooligosaccharide [91], and *O. mykiss* fed with alginate [124] and chitosan [155]. This immune parameter was also higher in *S. salar*, *H. huso* and *D. labrax* fed diet with alginate [46,100,107], in *C. gariepinus*, *P. fulvidraco* and *L. rohita* fed diet with fucoidan [73,128,129], in *M. cephalus* fed diet with ulvan [160], in *P. bocourti* fed diet with agar [71,215], in *C. mrigala* and *C. catla* fed diet with chitin [75,78], in *L. rohita*, *P. olivaceus*, *R. canadum*, *L. calcarifer* and *M. anguillicaudates* fed a diet with chitosan [90,108,113,117,134], in *T. ovatus*, *P. hypopthalmus* and *M. salmoides* fed diet with chitooligosaccharide [115,131,159], in *L. vannamei* and *F. chinensis* fed with alginate and fucoidan [50,54,92], in *A. japonicus* fed diets containing alginate [49], fucoidan [55], and carrageenan [59]. The alternative complement pathway (ACH_{50}) is known as one of the effective innate immune defence mechanisms which protect the aquatic animals against different types of bacteria [214], it can be activated by different immunostimulants including polysaccharides (Tale 2). The enhanced ACH_{50} have been observed in *C. carpio* fed with alginate, carrageenan, alginate and chitosan supplemented diets [16,80,120,121,169,170]. Further, *O. niloticus*, *D. labrax*, *P. bocouri, C. auratus*, *O. mykiss*, *C. mrigala*, *S. aurata*, *E. coioides*, *E. fuscoguttatus* and *E. bruneus* fed on diets incorporated with alginate, chitin, agar, chitin and chitosan showed higher ACH_{50} [2,15,52,61,62,67,71,75,88,100,104,140,175,180].

Antiprotease (APA), mainly α_1-antiproteinase and α_2-macroglobulin (MGB) are protease inhibitors exert a role in defence mechanism against pathogens, which secrete the protease enzyme [216]. Antiprotease present in the serum of animals which regulates the body fluid homeostasis [217]. The MDPs (chitin and chitosan) mediated alterations of APA and MGB activity has been reported in *E. bruneus* [62]. Phagocytosis (PHA) is the most important primary defence mechanism of the innate immunity of animals, and together with humoral components it constitutes the first-line of protection against invading pathogens. Phagocytes (monocytes/macrophages and neutrophils) engulf the microorganisms and kill them by degranulation, metabolic activation and release of microbicidal oxygen and nitrogen reactive species [218]. The significant elevations in PHA and respiratory burst activity (RBA) have been noted in *O. niloticus* fed in alginate [16,58,120,121], fucoidan [177], ulvan [130], chitosan [80], chitooligosaccharide [91] included diets. Dietary supplementation of alginate [170], fucoidan [128], carrageenan [169], chitin [75], chitosan [53,76,106,197], chitooligosaccharide [116] effectively enhanced PHA and RBA in different species of carp (*C. carpio*, *C. idellus*, *C. mrigala* and *L. rohita*). The enhanced PHA and RBA were reported in grouper (*E. bruneus*, *E. fuscoguttatus* and *E. coioides*) fed diets with alginate [15,52,88,104,140,175], chitin [61,62]. The shrimp species, such as *L. vannamei* and *P. monodon* fed on diets with alginate [48,92,93,172], fucoidan [123,139,149,198], carrageenan [122,142], ulvan [82,200], chitin [171] and seagrass crude polysaccharides [95] showed significantly elevated RBA and PHA. *A. japonicus* showed an improvement of PHA and RBA fed diets with alginate [18], ulvan [81], and chitooligosaccharide [133] have been reported. The improved PHA and RBA have also been observed in

Table 3
Uses of marine-derived polysaccharides on shrimp aquaculture.

Marine-derived polysaccharides	shrimp species	Doses	Duration of experiment	Growth performance and survival[a,b]	Biochemical and haemato-immunological parameters[a,b]	Disease resistance	References
Alginate							
	Litopenaeus vannamei	10–50 μg g^{-1}	6 days	SUR (↑)	THC, DHC, ProPO, RBA, PHA (↑)	*V. alginolyticus*	[48]
	L. vannamei	0.5–2.0 g kg^{-1}	150 days	SUR (↑)	ProPO, RBA, SOD (↑) GPx (↓)	*V. alginolyticus*	[172]
	L. vannamei	10–20 g kg^{-1}	30 days	SUR (↑)	THC, RBA, LYZ, PE, ProPO, SWDP (↑)	n.a.	[92]
	Penaeus monodon	1.5–2.0 g kg^{-1}	150 days	n.a.	SOD, βGBP, PE, cyt-SOD, PA-5, SWDP (↑) RBA (↓) THC, ProPO (↔)	n.a.	[14]
	P. monodon	0.001 g kg^{-1}	5 days	n.a.	EP, TLP, LHR (↑)	n.a.	[147]
	P. monodon	0.0001–0.004 g kg^{-1}	20 days	SUR (↑) MOR (↓)	n.a.	White spot syndrome virus	[68]
	P. monodon	1–3 g kg^{-1}	45 days	SUR (↑)	THC, ProPO, RBA, SOD, PHA (↑)	*V. parahaemolyticus*	[93]
	P. monodon	0.0005–0.004 g kg^{-1}	35 days	SUR, WG, SGR, FCR (↑)	THC, O_2^-, ProPO (↑)	White spot syndrome virus	[161]
Fucoidan							
	Fenneropenaeus chinensis	0.5–20 g kg^{-1}	14 days	MOR (↓)	THC, Propo, LYZ (↑) SOD (↔)	*V. harveyi*	[50]
	Marsupenaeus japonicus	0.0001–0.001 g kg^{-1}	56 days	WG, PR, SGR (↑) FCR (↓)	THC, Propo, SBA (↑)	*V. alginolyticus*	[144]
	P. japonicus	0.0001–0.001 g kg^{-1}	n.a.	SUR (↑)	n.a.	*V. harveyi*	[145]
	L. vannamei	1–2 g kg^{-1}	14 days	n.a.	LYZ, Propo, SOD, ACP (↑)	n.a.	[54]
	M. rosenbergii	0.0001–0.0005gkg^{-1}	28 days	SUR, WG, FCR (↑)	THC, Propo (↑)	White spot syndrome virus	[157]
	L. vannamei	3.5 g kg^{-1}	1 day	SUR (↑)	LAC, TP (↓) GLU (↔)	*V. campbellii*	[176]
	L. vannamei	0.0001–0.0004gkg^{-1}	21 days	SUR (↑)	THC, Propo, RBA (↑)	*V. alginolyticus*	[149]
	L. vannamei	3 g kg^{-1}	15 days	SUR (↑) MOR (↓)	THC, Propo, SOD, TGs (↑)	White spot syndrome virus	[87]
	P. monodon	0.0001–0.0004gkg^{-1}	10 days	SUR (↑)	ABA, PHA (↑)	White spot syndrome virus	[139]
	P. monodon	0.0005–0.010 g kg^{-1}	30 days	SUR, WG, SGR, PER (↑) FCR (↓)	n.a.	*V. harveyi*	[143]
	P. monodon	0.0001–0.0004gkg^{-1}	20 days	MOR (↓)	n.a.	White spot syndrome virus	[150]
	P. monodon	1–3 g kg^{-1}	45 days	MOR (↓)	THC, Propo, RBA, SOD, PHA (↑)	White spot syndrome virus	[198]
	P. monodon	2.0 g kg^{-1}	10 days	SUR (↓)	PHA, ABA (↓)	*V. harveyi*	[70]
	P. monodon	1–3 g kg^{-1}	60 days	WG (↑) MOR (↓)	THC, Propo, RBA, SOD, PHA, BCA (↑)	*V. parahaemolyticus*	[123]
	P. monodon	0.0001–0.0004gkg^{-1}	1 day	WG, SGR (↑) MOR (↓)	n.a.	*V. parahaemolyticus*	[151]
Carrageenan							
	L. vannamei	6 μg g^{-1}	5 days	SUR (↑)	THC, Propo, RBA, PHA (↑)	*V. alginolyticus*	[142]
	L. vannamei	0.5–2.0 g kg^{-1}	21 days	SUR (↑)	HPTs, THC, PHA (↑)	*V. alginolyticus*	[122]
Laminarin							
	F. chinensis	0.0002 g kg^{-1}	3 h	n.a.	THC, PC (↑)	n.a.	[173]
Ulvan							
	P. monodon	2–8 g kg^{-1}	14 days	SUR (↑)	THC, DHC, Propo (↑)	White spot syndrome virus	[57]
	P. monodon	0.0005–0.0015gkg^{-1}	14 days	SUR (↑)	THC, RBA, Propo (↑)	White spot syndrome virus	[200]
	P. monodon	0.0005–0.0015gkg^{-1}	56 days	FI, SGR, SUR (↔)	PPV (↑)	*V. harveyi*	[154]
	P. monodon and *L. vannamei*	0.5–1.5 g kg^{-1}	21 days	n.a.	THC, RBA, Propo (↑)	n.a.	[82]
Galactan							
	P. monodon	10–2000 μg ml^{-1}	1 day	n.a.	CPE, CV, VL (↓)	White spot syndrome virus	[153]
	P. monodon	100 and 200 μgml^{-1}	7 days	MOR (↓)	THC, O_2^-, SOD, Propo (↑)	White spot syndrome virus	[152]
	P. vannamei	5–20 g kg^{-1}	7 days	MOR (↓)	βGBP, IRG, AMP (↑)	*V. parahaemolyticus*	[94]
	P. vannamei	50 mg ml^{-1}	n.a.	n.a.	βGBP, AMP, Propo, (↑)	n.a.	[156]
Chitin and its derivatives							
	Macrobrachium rosenbergii	2.5–10 g kg^{-1}	n.a.	SUR (↑)	ABA (↑)	*Vibrio* spp.	[221]
	M. rosenbergii	50–100 g kg^{-1}	45 days	WG, SGR, FCR, SUR (↑)	n.a.	n.a.	[163]

(*continued on next page*)

Table 3 (*continued*)

Marine-derived polysaccharides	shrimp species	Doses	Duration of experiment	Growth performance and survival[a,b]	Biochemical and haemato-immunological parameters[a,b]	Disease resistance	References
	M. lanchesteri	250–750 g kg^{-1}	75 days	TW, SUR, NM, AW (↑)	n.a.	n.a.	[167]
	M. tenellum	5–250 g kg^{-1}	60 days	WG, FER, SGR (↑) SUR (↔)	EZA (↑)	n.a.	[132]
	L. vannamei	4–8 μg g^{-1}	6 days	SUR (↑)	THC, Propo, RBA, SOD, PHA (↑)	*V. alginolyticus*	[171]
	L. vannamei	125–2000 mg kg^{-1}	56 days	WG, SGR, FCE, SUR (↔)	TC, LDL-C (↔)	n.a.	[141]
	L. vannamei	0.5–4 gkg^{-1}	23 days	FBW, WG, SGR, SUR (↑)	n.a.	n.a.	[189]
	P. monodon	40–160 g kg^{-1}	50 days	SGR, FCR, SUR (↔)	CHI (↓)	n.a.	[162]
	P. monodon	10–50 g kg^{-1}	56 days	WG, PER (↑)	$ADC_{Protein}$, ADC_{Lipid} (↓)	n.a.	[97]
	P. monodon	1–10 g kg^{-1}	4 days	MOR (↓)	n.a.	*Vibrio* spp.	[51]
	P. monodon	n.a.	70 days	FBW, WG, BG, SUR (↑)	TAS, GSH-Px, MDA (↑) SOD, DO (↓)	n.a.	[118]
	P. monodon	0.5–4 g kg^{-1}	60 days	FBW, WG, BG, SUR (↑)	TC, TG, ALT, AST, (↑) MDA, THC, CBP (↓)	n.a.	[190]
Seagrass polysaccharides							
	P. monodon	0.25–1.0 g kg^{-1}	21 days	SUR (↑)	THC, TP, Propo, RBA (↑)	White spot syndrome virus	[95]

n.a-not available.

[a] **ABA:** antibacterial activity, **ACP:** acid phosphatase, **ADC_{lipid}:** lipid digestibility, **$ADC_{protein}$:** protein digestibility, **ALT:** alanine, aminotransferase, **AMP:** antimicrobial peptide, **AST:** aspartate aminotransferase, **BCA:** bactericidal activity, **CBP:** carbonyl protein, **CHI:** Chitinase activity, **CPE:** cytopathic effect, **CV:** cell viability, **Cyt-SOD:** cytosolic-superoxide dismutase, **DHC:** differential haemocyte counts, **DO:** dissolved oxygen, **EP:** egg production, **EZa:** enzyme activity, **FC:** fat content, **Glu:** glucose, **GPx:** glutathione peroxidase, **HPTs:** haematopoietic tissues, **IRG:** immune related genes, **LAB:** lactic acid bacteria, **LDL-C:** low density lipoprotein-cholesterol, **LHR:** larvae hatching rate, **LYZ:** lysozyme activity, **MDA:** malondialdehyde activity, **MOI:** moisture, **NFE:** nitrogen free content, **O_2^-:** superoxide anion production, **PA-5:** penaeidin-5, **PC:** protein concentration, **PE:** peroxinectin, **PHA:** phagocytic activity, **PPV:** protein productive value, **ProPO:** prophenoloxidase activity, **RBA:** respiratory burst activity, **SBA:** serum bactericidal activity, **SOD:** superoxide dismutase, **SWAP:** domain protein, **TAS:** total antioxidant status, **TC:** total cholesterol, **TG:** triglyceride, **TGs:** transglutaminase, **THC:** total haemocyte counts, **TLP:** total larvae production, **TP:** total protein, **VL:** viral load, **βGBP:** β-glucan binding protein.

[b] Variation in experimental shrimp compared to controls: (↑) significant increase; (↓) significant decrease; (↔) no significant changes.

Table 4
Uses of marine-derived polysaccharides on other aquatic animals.

Marine-derived polysaccharides	Aquatic animals	Doses	Duration of experiment	Growth performance and survival[a,b]	Biochemical and haemato-immunological parameters[a,b]	Disease resistance	References
Alginate							
	Apostichopus japonicus	1 g kg^{-1}	40 days	n.a.	POD, ACP, ALP, LYZ (↑)	n.a.	[49]
	A. japonicus	150 g kg^{-1}	70 days	SUR, WG (↑)	BCP (↑)	n.a.	[165]
	A. japonicus	50–400 μg ml^{-1}	1 day	n.a.	PHA, ROS, LYZ, PO, NOS, ACP (↑)	n.a.	[18]
	Haliotis diversicolor	1.0–3.0 g kg^{-1}	14 days	RSP (↑)	ProPO, RBA, SOD, PHA (↑)	*V. parahaemolyticus*	[69]
Fucoidan							
	A. japonicus	5–20 g kg^{-1}	15 days	n.a.	ACP, ALP, LYZ, SOD (↑)	n.a.	[55]
Carrageenan							
	A. japonicus	10 g kg^{-1}	3 days	n.a.	SOD, LYZ, ALP (↑)	n.a.	[59]
Ulvan							
	A. japonicus	0.5–2.0 g kg^{-1}	6 days	MOR (↓)	PHA, RBA, ACP, ALP, CAT, SOD (↑) TCC (↔)	*V. splendidus*	[81]
Chitin and its derivatives							
	Carcinus maenas	50–100 g kg^{-1}	77days	MOR (↓)	THC, PHA (↔)	*V. alginolyticus*	[164]
	Astacus leptodactylus	100–400 g kg^{-1}	60 days	FW, WG, SGR, LG, FCR, SUR (↑)	n.a.	n.a.	[166]
	Procambarus clarkia	5–15 mg g^{-1}	28 days	RPS (↑) MOR (↓)	THC, Propo, SOD (↑)	White spot syndrome virus	[146]
	P. clarkia	5–15 g kg^{-1}	60 days	n.a.	ALP, CAT (↑) GLU (↓)	n.a.	[119]
	P. clarkia	1–20 mg g^{-1}	12 days	SUR (↑)	Propo, SOD, THC (↑)	White spot syndrome virus	[158]
	A. japonicus	0.15–1.2 g kg^{-1}	56 days	MOR (↓)	PHA, RBA, ACP, ALP (↑)	*V. splendidus*	[133]

n.a-not available.

[a] **ACP**: acid phosphatase, **ALP**: alkaline phosphate, **BPC:** body biochemical composition, **CAT:** catalyse, **GLU:** glucose, **LYZ**: lysozyme activity, **NOS:** nitric acid synthase, **PHA:** phagocytic activity, **POD:** Peroxidase activity, **Propo:** prophenoloxidase activity, **RBA:** respiratory burst activity, **ROS:** reactive oxygen species, **SOD:** superoxide dismutase activity, **TCC:** total coelomocyte counts, **THC:** total haemocyte counts.

[b] Variation in experimental animals compared to controls: (↑) significant increase; (↓) significant decrease; (↔) no significant changes.

Clarias spp., *S. ocellatus* and *H. diversicolor* fed diet with alginate [69,72,83], *C. gariepinus* and *P. fulvidraco* fed diet with fucoidan [73,129], *M. cephalus* fed diet with ulvan [160], *P. bocourti* fed diet with agar [215], *S. aurata* fed diet with chitin [136,137,180], *C. auratus*, *P. olivaceus* and *L. calcarifer* fed diet with chitosan [2,113,134], *O. mykiss*, *S. maximus*, *P. hypophthalmus* and *M. salmoides* fed diet with chitooligosaccharide [114,131,159,203]. The release of myeloperoxide enzymes (MPO) by azurophilic granules of neutrophils is measured also through the serum peroxidase activity. A significant increase in these enzymes has been reported in *L. rohita*, *E. bruneus* and *P. olivaceus* fed diets incorporated with fucoidan, chitin and chitosan respectively [61,62,128,134].

In crustaceans, phenoloxidase (PO) in hemocytes is the terminal enzyme in the prophenoloxidase (proPO) system and can be an indicator to evaluate the health status [219]. The proPO cascade has a main role in melanisation and seems to contribute in the host defence by augmenting phagocytosis, nodule formation, encapsulation and hemocyte locomotion. Different type of MDPs has been reported to enhance PO in shrimps and crayfish (Tables 3 and 4). PO was elevated in *L. vannamei* and *P. monodon* fed diets with alginate [14,48,92,93,161,172], fucoidan [54,87,123,149,198], carrageenan [142], ulvan [57,82,200], galactan [152,156], chitin [171] and seagrass crude polysaccharides [95]. Positive effects on these enzymes have been also exhibited by alginate, fucoidan and chitosan fed to *H. diversicolor*, *F. chinensis*, *M. japonicus*, *M. rosenbergii* and *P. clarkia* [50,69,144,146,157,158].

11.2. Specific immune response

The supplementation of MDPs in fish, shrimp and other aquatic animals in association with infections has been reported to enhance the adaptive/specific immune response by improving the synthesis of specific antibodies (Table 2). Mendoza Rodriguez et al. [83] observed an enhancing level of immunoglobulin (Ig) in *S. ocellatus* fed with alginate diet. Feeds with fucoidan strongly enhanced the Ig production of *L. rohita* infected with *A. hydrophila* has also been reported [128].

12. Effects on resistance to infection

12.1. Bacterial infections

It has been widely accepted that MDPs can increase the resistance of fish, shrimp and other aquatic species against bacterial diseases by improving their overall immunostimulatory effects (Tables 2–4). Dietary supplementation with fucoidan [84,128], chitin [102], chitosan [2,76,103,106,117,155,197,220], chitooligosaccharide [116], alginate [168,170] significantly enhanced survival of different carp species (*C. carpio*, *C. idellus*, *C. mrigala* and *L. rohita*) against the pathogen *A. hydrophila*, *A. veronii* and *E. tarda*. Similarly, diet with fucoidan [129] in *P. fulvidraco*, diet with agar [71,215] in *P. bocourti*, diet with chitosan [80,85] in *O. niloticus* and *D. labrax*, diet with chitooligosaccharide [77,131,203] in *O. mykiss*, *O. niloticus* and *M. salmoides*, diets with chitin [17] and chitosan [182] in *S. salar* and *S. fontinalis* showed enhanced disease resistance against *A. hydrophila* and *A. salmonicida*. Similarly, dietary administration of alginate [104,175] in groupers (*E. bruneus*, *E. fuscoguttatus* and *E. coioides*) and *H. diversicolor* [69], chitin [17,61,133,164] in *E. bruneus*, *C. maenas*, *S. salar* and *A. japonicus*, chitosan [108,113] in *R. canadum* and *L. calcarifer*, chitooligosaccharide [115] in *T. ovatus*, chitin nanoparticles [86,191] in *L. calcarifer* and *D. labrax* and ulvan [81] in *A. japonicus* had showed significant enhancement of LYZ and bactericidal activities (BCA) led to potential prevention against *V. alginolyticus*, *V. harveyi*, *V. parahaemolyticus*, *V. anguillarum* and *V. splendidus* infections. Further, *S. maximus* and *P. hypophthalmus* fed a diet with chitooligosaccharide showed significant resistance to *E. tarda* and *E. ictaluri* [114,159]. Van Doan et al. [16,120,121] reported that *O. niloticus* fed a diet with alginate showed significantly reduced mortality when infected with *S. agalactiae*. Moreover, diet supplemented with alginate increased the survival rate in groupers (*E. bruneus*, *E. fuscoguttatus* and *E. coioides*) challenged against *Streptococcus* sp., and *S. iniae* infections [15,140]. Diets with alginate [88] and ulvan [160] yielded high survival rate of *E. coioides* and *M. cephalus* against *Photobacterium damselae* subsp. *piscicida* infection. Effects of MDPs on bacterial challenge in crustaceans have also been reported. Alginate [48,93,172], fucoidan [50,70,94,123,143–145,149,151,176], carrageenan [122,142], ulvan [155] and chitin [51,221] supplemented diets showed significant resistance of *L. vannamei*, *P. monodon*, *M. japonicus*, *M. rosenbergii* against *V. alginolyticus*, *V. harveyi*, *V. parahaemolyticus* and *V. campbelli* by enhancing the lysozyme, complement and bactericidal activity.

12.2. Viral infections

Marine-derived polysaccharides are also capable of reducing viral infections (Tables 3 and 4). Oral supplementation of alginate [68,161], fucoidan [139,150,198], ulvan [57,200], galactan [152,153] and seagrass crude polysaccharides [95] clearly showed the enhanced resistance of *P. monodon* against the viral pathogen white spot syndrome virus (WSSV). Moreover, a diet with fucoidan protected *L. vannamei* and *M. rosenbergii* against WSSV infection [87,157]. Furthermore, oral administration of chitin reduced the prevalence of infection caused by WSSV in *P. clarkia* [146,158].

12.3. Fugal and parasitic infections

The information about the MDPs control of fungal and parasitic infections is limited (Table 2). Dietary supplementation with chitin demonstrated a restorative effect in *C. mrigala* experimentally infected with the fungus, *A. invadans* [75]. Dietary administration of chitin reduced the mortality of *E. bruneus* infected with the protozoan parasite, *P. dicentrarchi* [62]. In context, *C. carpio* fed with chitosan had showed significantly reduced infestation of *Ptychobothrium* sp., [186].

13. Conclusion and future perspectives

Infectious diseases represent the main problem for the development of the aquaculture industry as they cause significant economic losses inasmuch as they restrict the productivity and need the use of control techniques that are often very expensive. However, indiscriminate administration of antibiotic and vaccines in aquaculture practices leads to the selection of antibiotic-resistant bacterial strains as well as the accumulation of chemical deposits in water and animal tissues, which may cause the adverse effect to the environment and be potentially dangerous for consumers. In this context, MDPs seem to represent a promising tool, complementary to vaccine and antibiotics and can be used to increase growth performance and food absorption, immune response, disease resistance, reduced microbial activity of different species of fish and shrimp and other aquatic animals which permits us to conclude that these polysaccharides are a functional natural feed additive used in a variety of ways in high, medium and low dose manner. It causes improved health condition of aquatic animals and increases productivity, thus providing a great potential which can be applied in aquaculture industry and finally there may also be health benefits for consumers. However, the role of MDPs on the gut physiology and immune gene expression on aquatic animals have need to be studied to improve the sustainable aquaculture production.

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