Seaweed Polysaccharides in Pigs

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Keywords: pig ; polysaccharides ; prebiotics ; seaweed

1. Overview

To ensure environmental sustainability, according to the European Green Deal and to boost the One Health concept, it is essential to improve animals' health and adopt sustainable and natural feed ingredients. Over the past decade, prebiotics have been used as an alternative approach in order to reduce the use of antimicrobials, by positively affecting the gut microbiota and decreasing the onset of several enteric diseases in pig. However, dietary supplementation with seaweed polysaccharides as prebiotics has gained attention in recent years. Seaweeds or marine macroalgae contain several polysaccharides: laminarin, fucoidan, and alginates are found in brown seaweeds, carrageenan in red seaweeds, and ulvan in green seaweeds. The present review focuses on studies evaluating dietary seaweed polysaccharide supplementation in pig used as prebiotics to positively modulate gut health and microbiota composition.

2. Background

Gut health, which is described as a generalized condition of homeostasis in the gastrointestinal tract [1], has been recognized as playing a key role in maintaining pig health. In fact, the gut plays an important role in efficient feed digestion and absorption, for the protection of the gut barrier, the microbiota composition, and the improvement in the immune status [2]. In fact, commensal bacteria such as Lactobacilli and Bifidobacteria are necessary to sustain the host immune system, protecting against the colonization of opportunistic pathogens [3].

Since the ban on in-feed antibiotics, reliable dietary interventions are needed that are capable of sustaining pig performance and improving gut health, by minimizing the use of antimicrobials. A large amount of evidence has reported the beneficial effects of some feed ingredients or additives in modulating gut health and microbiota in pig.

The review by Xiong et al. [2] focused on the effects of several feed ingredients or additives such as functional amino acids, natural extracts, and short-chain fatty acids and prebiotics on gut health in weaned pigs.

Over the past few decades, prebiotics have been used as an alternative approach aimed at reducing the use of antimicrobials, by positively affecting the gut microbiota and decreasing the onset of several enteric diseases in pig [4]. However, dietary supplementation with seaweed polysaccharides as prebiotics, has also gained attention in recent years. In fact, natural bioactive compounds have been considered as attractive dietary interventions in pig in order to ensure environmental sustainability, in line with the European Green Deal plan and to improve animal health according to the One Health approach.

Marine macroalgae, or seaweeds, are classified as brown algae (Phaeophyceae), red algae (Rhodophyta), and green algae (Chlorophyta) and include thousands of species. The chemical composition and the bioactive metabolite content of several species have been extensively studied, along with the variations related to species and genera, harvesting season, environmental conditions, and geographical location [5][6]. Seaweeds also contain large amounts of carboxylated and sulfated polysaccharides, with important functions for the macroalgal cells including structural and energy storage [7]. Seaweed polysaccharides are safe, environmental-friendly, and economical natural polymers. Seaweed polysaccharides, such as fucoidan, laminarin, ulvan, carrageenan, and alginates, show several biological activities in vitro and in vivo studies [8][9]. In fact, polysaccharides and oligosaccharides originating from seaweeds have been shown to regulate intestinal metabolism and fermentation and reduce the adhesion of pathogenic bacteria [10]. Several seaweed polysaccharides have also shown anti-inflammatory, antiviral, and antioxidant activities [11]. Considering the above mentioned properties, the present paper reviews the prebiotic effects of seaweed polysaccharides in pig nutrition.

3. Seaweed Polysaccharides

The polysaccharides contained in brown, red, and green seaweeds present different bioactive molecules such as fucoidan, laminarin, alginate, ulvan, and carrageenan, which are reported in Table 1.

Table 1. Polysaccharides and monosaccharides constituent of brown, green, and red seaweeds.

Chemical Constituent	Brown Seaweed	Green Seaweed	Red Seaweed
Polysaccharides	**alginate, laminarin, fucoidan (sulphated), cellulose, mannitol**	**ulvan (sulphated), mannan, galactans (sulphated), xylans, starch, cellulose, lignin**	**carrageenans (sulphated), agar (sulphated), glucans (floridean starch), cellulose, lignin, funoran**
Monosaccharides	**glucose, galactose, fucose, xylose, uronic acid, mannuronic acid, guluronic acid, glucuronic acid**	**glucose, mannose, rhamnose, xylose, uronic acid, glucuronic acid**	**glucose, galactose, agarose**
References	[12][13]	[12][13]	[12][13]

The yield of seaweed polysaccharides varies in relation to the species-growing conditions, extraction method, such as solvent concentration and extraction time [14]. The polysaccharide content of brown, red, and green seaweeds is reported in Table 2. The total polysaccharide content in seaweeds is highly variable, fluctuating from 4 to 80% of dry matter (DM), according to the data of Lafarga et al. [12].

In green seaweeds, the content ranges from 15 to 65% of DM with the highest value for Ulva spp., in red seaweeds from 53 to 66% of DM with the highest value in Chondrus crispus, and in brown seaweeds from 10 to 66% DM with the highest amount in Ascophyllum nodosum and Saccharina spp. [15].

Carrageenans and agars are the two main polysaccharides in red seaweeds, but porphyran and xylan have also been observed [16]. Carrageenans are sulfated polysaccharides, composed of d-galactose units, with a structural role, similar to cellulose in plants, and are present in some red algae, such as Chondrus, Gigartina, and Hypnea [17], with the highest amount in Chondrus and Kappaphycus spp. [18]. Agar is largely observed in the Gelidium and Gracilaria spp. and is composed of agarose and agaropectin [19]. Fucoidans, alginates, and laminarin are the main polysaccharides in brown seaweeds.

Alginates are the main cell wall polysaccharides in brown algae, such as Laminaria spp., Fucus spp., Ascophyllum nodosum, and Macrocystis pyrifera [20]. Besides alginates, fucoidans are cell wall water-soluble polysaccharides in brown seaweeds, containing L-fucose and sulfate groups, in addition to monosaccharides such as mannose, glucose, xylose, and glucuronic acid [21].

Table 2. Polysaccharides composition of brown, red, and green seaweed (g kg^{-1} DM) [1].

Seaweed	Polysaccharides, %	Alginates	Carragenan	Fucoidan	Laminarin	Ulvan	References
Brown							
Ascophillum nodosus	**62 (42–70)**	**285 (240–330)**	**-**	**75 (11–120)**	**118 (12–120)**	**-**	[8][18][22][23][24][25]
Laminaria hyperborea	**39.9 (14.4–65.5)**	**215 (22–408)**	**-**	**30 (20–40)**	**125 (0–320)**	**-**	[8][18][26][27][28]
Laminaria digitata	**57.3 (44–70.7)**	**435 (350–520)**	**-**	**49.5 (22–112)**	**120 (0–350)**	**-**	[8][18][26][27][29][30][31]
Laminaria sp. *	**45 (13–77)**	**309 (225–343)**	**-**	**147.5 (22–550)**	**153 (62.4–340)**	**-**	[8][26][29][32][33][34][35]
Fucus sp. #	**57 (34.5–66)**	**162**	**-**	**105 (11–200)**	**2.3 (0.4–3.8)**	**-**	[18][23][24][27][34][36][37][38]

Seaweed	Polysaccharides, %	Alginates	Carragenan	Fucoidan	Laminarin	Ulvan	References
Sargassum sp. ‡	36 (4–68)	296 (93–499)	-	38 (31–45)	3 (0–6)	-	[18][34][36]
Saccharina sp. **	69 (58–80)	242.5 (200–285)	-	33 (13–80)	97.5 (0–330)	-	[5][8][18][23][27][29][39]
Undaria pinnafitica	40 (35–45)	425 (340–510)	-	219 (30–690)	30	-	[8][18][29][40]
Red		-	-	-	-	-	
Chondrus crispus	60.5 (55–66)	-	439.5 (338–510)	-	-	-	[18][34][41]
Kappaphycus alvarezii	58 (53.5–64)	-	448.5 (187–756)	-	-	-	[32][41][42][43]
Green						-	
Ulva sp. §	42 (15–65)	-	-	-	-	176 (11–400)	[18][34][44][45][46][47][48]

[1] Data are reported as mean values and range (minimum-maximum). * Values from Laminaria claustonii and japonica. # values from Fucus vesciculosus, serratus, spiralys. ‡ Values from Sargassum patens, hemifhyllum, henslowianum. ** Values from Saccharina longicruris, latissima, cichorioides, japonica, longissimi. § Values from Ulva armoricana, lactuca, intestinalis, meridionalis, pertusa. - Polysaccharides not present in the considered seaweed.

Laminarin, also called laminaran, is a storage polysaccharide in brown seaweeds which is composed of (1–3)-β-d-glucan. The laminarin structure differs in the degree of branching and polymerization. The highest laminarin content is found in Laminaria spp. and Saccharina spp. (32% DM), however it is also present in small amounts in Ascophyllum, Fucus, and Undaria spp. [18]. Ulvan is the constituent of the cell wall of green seaweeds and is constituted by β-(1–4)-xyloglucan, glucuronan, and cellulose in a linear arrangement [49]. The ulvan content varies from 2.7% DM in Ulva flexuosa to 40% DM in Ulva Armoricana [48].

4. Seaweed Polysaccharides as Prebiotic

Carbohydrates, which are indigestible to hydrolytic enzymes and are fermentable, are considered as prebiotics. They must not be digested or adsorbed in the first tract of the gut, however they should be fermented in the colon by Lactobacillus and Bifidobacterium, enhancing their growth and decreasing the concentration of other invading pathogens in the large intestine [50]. Digestion can affect the seaweed polysaccharide activity as prebiotics. The first step is to verify the resistance to hydrolysis by acids and enzymes in in vitro conditions.

Laminarins from different seaweeds vary in terms of the structural characteristics such as the degree of polymerization and the presence of inter-chain hydrogen bonds. These complex structures are resistant to hydrolysis in the first tract of the gut and are studied as dietary fibers [51]. In brown seaweed, polysaccharide laminarins were indigestible in an in vitro model with hydrochloric acid and enzymes [52]. In addition, laminarin from Laminaria saccharina and digitata were fermented, producing short-chain fatty acids (SCFA) [53]. Another study reported that SCFA that are produced from the fermentation of Laminaria digitata and Undaria pinnatifida are not metabolized well compared to the sugar beet fibers [54].

5. Seaweed Polysaccharides as Prebiotics in Sows

The effects of algae polysaccharides as prebiotics in sows have been evaluated by several authors.

The effects of polysaccharides in the gut are usually assessed by evaluating the SCFA content and the intestinal microbiota composition and/or the presence of beneficial bacteria [55]. The effects of dietary supplementation with seaweeds in sows can modulate the productive performances and health of lactating piglets, making them more resistant to pathogens.

6. Seaweed Polysaccharides as Prebiotics in Post Weaning Piglets

Weaning is a critical phase in pig production, often characterized by high antibiotic and microelement use. In fact, at weaning the gastrointestinal tract and immune system of piglets are not yet fully developed and the social, environmental, and physiological challenges, predispose the piglets to dysbiosis [56]. These challenges lead to a lower feed intake and growth rate and a high incidence of post-weaning diarrhea (PWD) due to the presence of enteric pathogenic bacteria [57].

In fact, at weaning, a lower Lactobacilli count has been observed, with a high growth of facultative anaerobes bacteria such as Enterobacteriaceae, Proteobacteriaceae, Clostridiaceae, and Prevotellaceae [56]. After weaning, structural and functional alterations of the small intestine have also been observed with negative effects on the absorptive capacity [58].

Feeding strategies in the post-weaning phase can reestablish the gut eubiosis that was lost at weaning, aimed at restoring the Lactobacillus count, promoting the growth of beneficial bacteria that boost the mucosal immune system and lowering the pathogenic bacteria proliferation [59].

The role of diet in the post weaning health status is widely recognized, in fact feed ingredients and additives can exert selective pressure on the gut microbiota. It has also been reported that dietary fermentable carbohydrates play a key role in positively affecting the intestinal microbiota of post-weaning piglets [60].

Several studies have evaluated the effects of seaweed polysaccharides as prebiotics in post weaning piglets.

The dietary inclusion of Ascophillum nodosum in the piglets' diet can reduce the Escherichia Coli content in the small intestine of weaned piglets [61]. The Lactobacillus/Escherichia coli ratio in the small intestine was shown to increase in the piglets receiving dietary seaweeds suggesting a helpful microbial modification. A reduction in the Enterobacteriaceae count was also observed. Similar data on gut health improvement have been observed with dietary supplementation with Laminaria spp.

Laminarin and fucoidan, as sources of seaweed polysaccharides with prebiotic effects, are able to decrease fecal Escherichia coli counts in the feces, thus improving post-weaning piglet health with a positive effect on growth performance and gain to feed ratio [62][63]. An improvement in Lactobacillus count has also been detected [62][64][65][66][67].

It has been also reported that laminarin, modifying the resident microbiota, may indirectly enhance mucin synthesis and secretion, as adherence of beneficial bacteria to mucosal epithelia up-regulates the mucin production. An enhancement of cytokine gene expression was also observed after a lipopolysaccharide (LPS) challenge [68].

Fucoidan also supports Lactobacillus growth with a positive effect on feed digestibility [69][68].

The increase in butyric acid reported in several studies, is usually related to carbohydrate fermentation which has a positive effect.

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