



Potential of Underutilized Marine Organisms for Aquaculture Feeds

Dedi Jusadi[†], Julie Ekasari^{*†}, Muhammad Agus Suprayudi, Mia Setiawati and Ichsan Achmad Fauzi

Department of Aquaculture, Faculty of Fisheries and Marine Sciences, Bogor Agricultural University, Bogor, Indonesia

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*Correspondence:

Julie Ekasari
j_ekasari@apps.ipb.ac.id

[†]These authors have contributed
equally to this work and share first
authorship

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The supply of land-based agricultural products as aquafeed raw materials is challenged by limitations on space and water, and by environmental damage. Marine environments offer a vast opportunity for the expansion of aquaculture, including the production of feed raw materials. Besides fishmeal and fish oil, which are generated from capture fisheries, the use of marine-based feed raw materials from aquaculture production is not yet in common practice. Here, we discuss the potential of underutilized marine organisms that can be cultured by extracting nutrients from their environment and are nutritionally compatible for use as alternative feed materials in aquaculture. We identify marine organisms such as blue and green mussels, *Ulva* spp., and microbial floc that are nutritionally suitable as aquafeed raw material and may further act as bioremediators. However, environmental factors that affect productivity and the risk of pollutant accumulations, which would potentially reduce the safety of aquaculture products for human consumption, may pose challenges to such applications of extractive organisms. Therefore, the development of pretreatment and processing technologies will be critical for improving the nutritional quality and safety of these raw materials for aquafeed production.

Keywords: aquafeed, bioremediation, extractive organisms, macroalgae, shellfish, microalgae

INTRODUCTION

Aquaculture is expected to meet the majority of the demand for seafood, given that capture fisheries have been in stagnation for the last few decades (FAO, 2020). However, the development of aquaculture production is challenged by limitations on pivotal resources such as space, water, and feed raw materials. Aquaculture products can be classified into two groups, i.e., fed organisms, which are cultured with the addition of external feed, and unfed organisms, which are cultured without the addition of external feed (Hua et al., 2019; FAO, 2020). At present, most aquaculture activities produce fed organisms that rely heavily on formulated feed. Thus, the increase in aquaculture production has a generally linear relationship with the increase in feed production (FAO, 2020). The inclusion of fishmeal and fish oil, a common source of protein and lipids in aquafeeds in decades, has substantially declined due to rising prices of these products and the sustainability concerns over the harvesting of small pelagic fish used to produce them (Hua et al., 2019). As a result, most raw materials in aquafeed are now agricultural products produced in terrestrial systems where water, space, and other environmental resources have become scarce. The marine ecosystem, on the other hand, offers vast opportunities for the production of produce seafood products and aquafeed raw materials (Gentry et al., 2017).

The intense competition for raw materials due to other human uses, which affects aquafeed supply, is a major motivation for the aquaculture sector to generate its own feed raw materials from marine sources. The demand for high-quality materials for various human-related applications has been increasing, creating more opportunities for the aquaculture sector to produce marine-based high-quality raw materials for various human needs, including other food-producing sectors such as livestock production. Aquafeed raw material exploration should focus on unfed marine organisms, which can act as bioremediators that extract waste nutrients from the environment and convert them into beneficial biomass that may be used as feed raw materials (Agarwal et al., 2020). Here, we discuss the potential use of some underutilized marine organisms as candidates for raw materials in aquafeed, with specific emphasis given to unfed low-trophic-level organisms such as shellfish, seaweed, and microorganisms.

SELECTION CRITERIA FOR AQUAFEED RAW MATERIALS

The following criteria should be considered when selecting appropriate aquafeed raw material: (1) nutritional value relative to the requirement of the cultured animal and its digestibility by the target animal; (2) the presence of antinutritional factors (ANFs) and contaminants; (3) supply reliability; and (4) price volatility (Glencross et al., 2020). The nutritional composition and digestibility of feed materials have synergistic effects on growth outcomes of fed aquaculture species. In addition, the physical and nutritional qualities of raw materials should also include their characteristics during manufacturing processes and how they affect the pellet quality (Turchini et al., 2019). High digestibility ensures high nutrient bioavailability and utilization by the animal. The presence of antinutritional factors, i.e., substances that could interfere with food utilization and negatively affect the health and production of animals, is an important factor determining the nutritional feasibility of a raw material for aquafeed (Francis et al., 2001). In addition, marine-origin raw material may carry the risk of contamination by heavy metals and toxins, with potential direct or indirect adverse effects on the fed organisms and final consumers. In the aquafeed industry, the use of materials with routine and consistent supply is critical to reduce the risks of fluctuations in product quality and specification, cross-contamination, and shortfalls in supply during manufacturing (Glencross et al., 2020). Thus, continuous supply of a particular raw material in bulk quantities should be one of the major considerations when selecting potential raw material for aquafeed. The price volatility of a raw material, which is strongly influenced by its supply and demand, is the main economic factor affecting profitability in aquafeed manufacturing. In the context of raw material production, the supply of a raw material in bulk at an affordable price implies that the culture productivity, i.e., production per unit of area or per unit of water, and the processing cost of the marine-origin raw material should be comparable to that for the production of existing terrestrial-based raw materials. How new raw materials influence the environmental and social

sustainability of aquafeeds are also critical considerations in the development of new feed products (Valenti et al., 2018). However, here, we focus on the technical potential of new ingredients as a first step for scoping novel raw materials of interest for the aquafeed industry.

POTENTIAL MARINE UNFED ORGANISMS AS FEED RAW MATERIALS

In this minireview, our focus is mainly given to macro- and microscopic organisms that are high in productivity and can be cultured by using nutrient waste or by-products, either in open marine environments or in enclosures in coastal areas. Based on these criteria, we identify some marine organisms that are potentially useful for aquafeed; these are classified into three groups: of animal, macroalgae, and microscopic origins (Table 1).

Animal-Origin Materials

Marine-animal-origin feed raw materials are mostly used as sources of essential amino acids and essential fatty acids for most aquaculture animals. There are at least three animal-origin materials that have the potential to be used as a protein source in aquafeed: mussels, artemia, and amphipods. These animals are low-trophic-level organisms that extract nutrients from primary producers such as microalgae and/or particulate organic matters in the aquatic environment. Mussels such as green (*Perna viridis*) and blue (*Mytilus edulis*) are extractive organisms that grow rapidly in nutrient-rich environments and act as bioremediator agents converting waste nutrients into the protein. Mussels contain considerably high protein [50–70% dry weight (DW)] and lipid (5–16% DW) levels, with comparable essential amino and fatty acids contents to those of fishmeal (Jusadi et al., 2020). A number of studies demonstrated that mussels are a promising protein source in aquafeed, with a reported maximum inclusion level of up to 25% (Weiß and Buck, 2017; Jusadi et al., 2020). From an ecological perspective, mussels have been considered to play some important roles in carbon fixation and mitigation of ocean eutrophication (for a detailed review, see Suplicy, 2020). *Artemia* nauplii have been used as an important live food in almost all aquaculture hatchery productions. However, the supply of *Artemia* nauplii has been heavily reliant on cysts collected from the wild. Thus, many efforts have been undertaken to culture *Artemia* to produce cysts. Moreover, the use of adult *Artemia* as feed has started to gain attention. *Artemia* can be cultured at a relatively high productivity (ca. 2 tons/ha/crop) in shallow ponds by using by-products or waste as their feed (Anh et al., 2009b). The protein content of *Artemia* biomass is relatively high, e.g., a range of 51–61% DW, with a lipid content ranging from 5 to 10% DW (Anh et al., 2009a). Amphipods are another small crustacean that can grow rapidly in nutrient-rich areas. A recent study by Herawati et al. (2020) showed that *Phronima* sp. cultured using microalgae and cow manure could be used as the sole food for Pacific white shrimp postlarvae.

TABLE 1 | Nutritional compositions of some underutilized marine organisms and its utilization as feed raw materials in aquaculture.

Material	Species	Protein (% DW)	Lipid (% DW)	Carbohydrate (% DW)	Fiber (% DW)	Ash (% DW)	Target species	Dietary inclusion (%)	References
Animal origin									
Mussels	<i>Mytillus edulis</i>	52–70	7–16	13	1.4	9–11	<i>Scophthalmus maximus, Solea solea, Salvelinus alpinus, Perca fluviatilis</i>	25	Mongile et al., 2015; Langeland et al., 2016; Weiß and Buck, 2017; Wagner et al., 2019
	<i>Perna viridis</i>	53.9	11.2		0.1	8.9	<i>Oreochromis niloticus</i>	10	Jusadi et al., 2020
Artemia	<i>Artemia biomass</i>	50.7–61.4	4.9–9.9		2.5–16.6	25.0	<i>Macrobrachium rosenbergii</i>	57.5–100	Anh et al., 2009a
Amphipods	<i>Phronima sp.</i>	40.3	15.1	10.0	8.9	17.2	<i>Litopenaeus vannamei</i>	100	Herawati et al., 2020
Macroalgal origin									
Chlorophyta	<i>Ulva lactuca</i>	11.5–32.2	0.5–6.1	43.5	9.1–15.0	24.4–33.2	<i>Clarias gariepinus, Sparus aurata, Oreochromis niloticus, Litopenaeus vannamei</i>	5–25	Abdel-Warith et al., 2016; Shpigel et al., 2017; Suryaningrum et al., 2017; Laramore et al., 2018; Guerreiro et al., 2019
	<i>Ulva rigida</i>	8.0–29.5	0.2–2.0	46.8–50.4	12.3	4.5–26.7	<i>Sparus aurata, Oreochromis niloticus, Cyprinus carpio, Onchorhynchus mykiss</i>	5–25	Diler et al., 2007; Ergün et al., 2009; Güroy et al., 2013; Vizcaino et al., 2016
	<i>Ulva sp.</i>	5.3	0.3–2.7		5.2–5.3	24.7–46.0	<i>Oreochromis niloticus, Litopenaeus vannamei, Scatophagus argus, Argyrosomus japonicus</i>	6–25	Silva et al., 2015; Madibana et al., 2017; Qiu et al., 2018; Yangthong and Ruensirikul, 2020
	<i>Caulerpa lentillifera</i>	19.4–29.2	0.8–2.9	44.0–53.5	4.1	16.6–29.6	<i>Oreochromis niloticus, Penaeus monodon</i>	5–20	Nagappan and Vairappan, 2014; Putri et al., 2017; Putra et al., 2019
	<i>Caulerpa racemosa</i>	17.3–30.0	1.8–2.1	42.7–52.8	3.1–3.3	22.2–26.7	<i>Penaeus monodon</i>		Nagappan and Vairappan, 2014; Puspitasari et al., 2019
Rhodophyta	<i>Gracilaria arcuata</i>	13.5	7.0			31.9	<i>Clarias gariepinus, Oreochromis niloticus,</i>	10	Al-Asgah et al., 2016; Younis et al., 2018
	<i>Gracilaria lemaneiformis</i>	18.9	0.5				<i>Acanthopagrus Schlegelii, Pagromus major</i>	3–15	Xuan et al., 2013, 2019
	<i>Gracilaria pygmaea</i>	16.7	1.0		1.2	29.5	<i>Onchorhynchus mykiss</i>	6	Sotoudeh and Jafari, 2017
	<i>Gracilaria cornea</i>	13.5	0.8	39.8		35.6	<i>Sparus aurata</i>	25	Vizcaino et al., 2016
Phaeophyta	<i>Macrocystis pyrifera</i>	6.1	0.7	44.2	10.5	31.1	<i>Litopenaeus vannamei, Onchorhynchus mykiss</i>	1.5–3.3	Cruz-Suárez et al., 2009; Dantagnan et al., 2009
	<i>Sargassum horneri</i>	13.2–17.2	0.5–1.3	63.0		11.7–19.4	<i>Acanthopagrus schlegelii, Scophthalmus maximus</i>	6–10	Shi et al., 2019; Wang et al., 2019
	<i>Sargassum illicifolium</i>	9.2	2.1	33.1	10.3	29.2	<i>Litopenaeus vannamei, Huso huso</i>	7.5–15	Hafezieh et al., 2014; Yeganeh and Adel, 2019

(Continued)

TABLE 1 | Continued

Material	Species	Protein (% DW)	Lipid (% DW)	Carbohydrate (% DW)	Fiber (% DW)	Ash (% DW)	Target species	Dietary inclusion (%)	References
Microscopic origin									
Microalgae	<i>Nannochloropsis oculata</i>	42.2	5.6		0.6		<i>Litopenaeus vannamei</i>	25	Gamboa-Delgado et al., 2019
	<i>Nannochloropsis granulata</i>	33.9	27.6	14.4		7.5	<i>Litopenaeus vannamei</i> , <i>Onchorhynchus mykiss</i>	26–29	Tibbetts et al., 2017
	<i>Nannochloropsis</i> sp.	33–51	18–20			35	<i>Marsupenaeus japonicus</i> , <i>Dicentrarchus labrax</i> , <i>Scophthalmus maximum</i>	7–10	Oswald et al., 2019; Qiao et al., 2019; Valente et al., 2019; Adissin et al., 2020
	<i>Chlorella vulgaris</i>	58.0–66.4	4.0–9.6	17.3	3.3	5.1–5.5	<i>Clarias gariepinus</i> , <i>Danio rerio</i>	0.6–30	Raji et al., 2018; Carneiro et al., 2020
	<i>Schizochytrium</i> sp.	11–16	51–70	19.4		3.8–4.4	<i>Ictalurus punctatus</i> , <i>Pagrus major</i> , <i>Salmo salar</i>	2–11	Li et al., 2009; Kousoulaki et al., 2016; Seong et al., 2019; Katerina et al., 2020
	<i>Tetraselmis suecica</i>	38.7	12.4	44.3			<i>Litopenaeus vannamei</i> , <i>Dicentrarchus labrax</i>	0.7–12	Messina et al., 2019; Sharawy et al., 2020
	<i>Tetraselmis</i> sp. (defatted)	40.6	1.3			14.6	<i>Sparus aurata</i>	10	Pereira et al., 2020
Cyanobacteria	<i>Isochrysis galbana</i>	23.2	36.6	34.5		1.7	<i>Trachinotus ovatus</i>	8.6	He et al., 2018
	<i>Arthrospira</i> sp.	59.4–63.2	2.2–7.0	15.0	1.2–3.2	4.1	<i>Litopenaeus vannamei</i> , <i>Lates calalifer</i> , <i>Onchorhynchus mykiss</i> , <i>Salmo salar</i> , <i>Clarias gariepinus</i>	25–50	Burr et al., 2012; Gamboa-Delgado et al., 2019; Raji et al., 2020; Van Vo et al., 2020
Bacteria	Biofloc meal	23.4–49.0	0.3–1.1	18.6–36.4	12.6	13.4–36.6	<i>Litopenaeus vannamei</i> , <i>Penaeus monodon</i>	12–15.7	Bauer et al., 2012; Simon et al., 2020

Materials of Macroalgal Origin

Some macroalgae (seaweeds) species have been studied intensively as feed raw materials, either as phyco-additives that contribute bioactive compounds such as flavonoids, prebiotics, and carotenoids, or as a source of macro- and micro-nutrients. Seaweeds are also known as effective nutrient biosorbents that remove various nutrients from their surrounding environment. Members of the genus *Ulva* spp. are those seaweeds with greatest potential for aquafeed raw materials. These green macroalgae (Chlorophyta) have a high annual productivity (ca. 838 g C/m²/year) (Chemodanov et al., 2017) and have the potential to be used as feed material and for other human uses. For instance, with its high total ammonia nitrogen (89%) and phosphate (44%) removal capacity (Kang et al., 2021), *U. pertusa* has the potential to be cultured as a phytoremediator in intensive fish or shrimp ponds, in coastal zones, and/or to be cultivated in integrated multitrophic aquaculture (IMTA) systems (Aníbal et al., 2014). The protein content of *Ulva* spp. may reach up to 32% DW, with a lipid content of <2% DW (Table 1). *Ulva* spp. also contains high levels of aspartic acid and glutamic acid as well as alanine and arginine. The apparent digestibility of *Ulva* spp. proteins by rainbow trout and tilapia is 75.6 and 63.4%, respectively (Pereira et al., 2012). Various species of *Ulva* have been studied as a feed material for some aquaculture species, with a maximum inclusion level recorded at 25% (Yangthong and Ruensirikul, 2020). *Gracilaria* sp. is one of the most commonly cultured red algae (Rhodophyta). Members of this genus has been consumed and used to produce agar and can contain protein up to 18.9% DW with a lipid content of <1% DW (Xuan et al., 2019). The protein digestibility of *Gracilaria vermiculophylla* was reported to be about 87.8 and 51.4% in rainbow trout and Nile tilapia, respectively (Pereira et al., 2012). The utilization of *Gracilaria* spp. for aquafeed has been tested in various aquaculture species, with the highest inclusion level reported in European seabass at about 25% (Vizcaino et al., 2016). Other studies of macroalgal genera in aquafeed have focused on some brown algae (Phaeophyta), such as *Macrocystis* spp., *Ascophyllum nodosum*, and *Sargassum* spp. The inclusion levels of these macroalgae groups, however, were reported to be lower relative to *Ulva* or *Gracilaria*. *Sargassum muticum*, for instance, contains relatively lower protein levels than *Ulva* and *Gracilaria*, at a range of 9–17% DW, with higher protein digestibility in Nile tilapia (71.2%) compared with that of *Gracilaria* sp. (Pereira et al., 2012).

Materials of Microscopic Origin

Materials of microscopic origin are derived from microorganisms such as microalgae, yeast, cyanobacteria, and bacteria. Microalgae contain various essential nutrients such as amino acids, fatty acids, and vitamins as well as bioactive compounds that are beneficial for both aquaculture animals and humans. Studies have recently demonstrated the possibility to generate microalgal biomass using wastewater, which might not suitable for human uses but could be used as a feed material (Dourou et al., 2018, 2020; Malibari et al., 2018). Among the extensively studied marine microalgae, several species that have a high potential as aquafeed raw materials include *Nannochloropsis*

spp., *Chlorella* spp., *Schizochytrium* spp., *Tetraselmis* spp., and *Isochrysis* spp. (Table 1). *Nannochloropsis* spp. are known as a source of n-3 highly unsaturated fatty acids (HUFAs) that can be cultured with high productivity (33.6–84.0 tons/ha/year) (Griffiths et al., 2012; Chauton et al., 2015). The members of this genus could be used as an aquafeed material with an inclusion level up to 82% (Gbadamosi and Lupatsch, 2018). A recent study showed that the use of defatted *Nannochloropsis oculata* (a by-product of oil extraction for nutraceuticals) and whole cells of *Schizochytrium* sp. to substitute fishmeal and fish oil in Nile tilapia diet resulted in a 48% higher final body weight and 8% lower feed cost per kilogram fish production (Sarker et al., 2020). *Arthrospira* (*Spirulina*) spp. are cyanobacteria with substantial productivity (20–90 tons/ha/year) that has been cultured and used as food and feed supplements (Soni et al., 2017). With the high capacity in removing phosphate (99.97%) and nitrate (81.10%) in water, this group of cyanobacteria has the potential to be cultured in integration with other aquaculture production as a bioremediator (Cardoso et al., 2020). Members of the genus *Arthrospira* are also known for their nutritional benefits. For example, *Arthrospira platensis* is reported to have a significantly high protein content (about 60% DW) (Van Vo et al., 2020) and various high-value bioactive compounds including vitamins, essential lipids, and natural pigments (phycocyanins) (Cuellar-Bermudez et al., 2015). *Arthrospira* spp. have been tested on various aquaculture species with the highest inclusion level recorded in African catfish, at about 30%, and may completely substitute fishmeal use (Raji et al., 2020). Although some marine yeast and bacteria have been identified recently, most of the studies involving these microorganisms as aquafeed raw materials are not specific to marine species. Commercially available bacterial meals are mainly produced from natural gas fermentation by using single or mixed species of methanotrophs (Jones et al., 2020), some of which can also be found in marine environment. Bacterial meal is a single-cell protein that can be used in the diet of various animals including aquaculture species (Øverland et al., 2010). A notable aquafeed raw material is biofloc meal, which mainly consists of a heterogenous mix of bacteria. Biofloc can be generated from fish or shrimp wastewater treatment and has a protein content in the range of 23–49% DW (Dantas et al., 2016). This material could be used in shrimp feed at an inclusion level up to 60% (Bauer et al., 2012; Promthale et al., 2019).

THE CHALLENGES OF UTILIZING MARINE-BASED ORGANISMS FOR AQUAFEED AND STRATEGIES TO ENHANCE UTILIZATION

The utilization of marine-based organisms for feed material is not without challenges. The use of each material is associated with specific challenges that may limit its use in aquafeeds; these include (1) nutritional composition and productivity, which may strongly depend on the environment; (2) risk of contamination by toxins and heavy metals; and (3) presence of antinutritional factors. The productivity and nutritional

composition of macroalgal- and microbial-based materials could be strongly dependent on the nutrient quantity and composition of the water, which are site and season specific (Mohy El-Din, 2019). Likewise, the productivity and nutritional composition of mussels could depend on the quantity of organic matter, microalgal composition, and the presence of stressors in their environment (Martino et al., 2019). This implies that site selection is an essential strategy to maintain high productivity and high quality of marine-based raw materials. Nutrient-rich environments are also associated with the higher possibility of toxin and heavy metal absorption by extractive marine organisms, which may reduce the safety of the raw materials (Torres et al., 2019). A recent study by Jusadi et al. (2020) demonstrated that accumulation of heavy metals in mussel meal could be alleviated by dietary supplementation of fulvic and humic acids at very low concentrations. Fulvic and humic acids are chelating agents that bind heavy metals to prevent their absorption by the fish, thus avoiding the accumulation of heavy metals in aquaculture organisms. van der Spiegel et al. (2013) suggested that some seaweeds may contain some hazards such as ANFs, dioxins, and pesticides that limit their use as feed and/or food materials. Fermentation and biorefinery technologies that have been well-developed in various food technologies could be applied to these materials to improve their nutritional value and to optimize nutrient digestibility as well as eliminate potential hazards (Bikker et al., 2016; Fleurence, 2016). While some of these raw materials, particularly those of macroalgal origin, are typically lower in protein than current sources; the development of protein concentrates for emerging ingredients may help bolster their use in future aquafeeds (Magnusson et al., 2019). Various hydrolytic processes could be applied to these materials to remove possible contaminants such as heavy metals and toxins to ensure their safety for the fed organisms and ultimately for human consumption (Torres et al., 2019).

CONCLUSIONS AND FUTURE DIRECTIONS

Marine-based feed materials are promising raw materials for aquafeed development. From a nutritional point of view, marine-based materials are relatively similar, if not superior, to terrestrial-origin materials. The production of unfed marine-based materials does not require freshwater and may enable the retrieval of waste nutrients from the environment, thus

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allowing more efficient use of nutrients, reducing the negative impacts of aquaculture on the environment, and promoting the sustainability of marine aquaculture in general. Some of the marine-based feed raw materials are already available commercially, such as seaweeds, microalgae, or bacteria meals; however, the price of these products is still high and is not competitive with conventional feed materials. Thus, more efforts are needed to promote the development of technologies for the production and processing of these materials to enable their commercial use. Further research on the environmental and nutritional requirements of these organisms are needed in order to improve productivity. More studies are also required to elucidate strategies to enhance the nutritional quality of the materials. The development of pretreatment and processing technologies is required to reduce the risks of contamination and antinutritional factors as well as to improve the nutritional quality of the products. Biorefinery technologies that could allow the utilization of all valuable constituents of a raw material in an economically feasible cascading process, with limited to zero waste, could be developed for the efficient use of the raw materials and for the production of high-quality materials for aquafeed production.

AUTHOR CONTRIBUTIONS

DJ was responsible for the conceptualization, data collection, and manuscript preparation. JE was responsible for data collection and manuscript preparation. MAS contributed to the analysis, interpretation of the data, and information as well as providing critical review to the manuscript in particular those sections relating to the criteria of aquafeed raw materials quality. MS was involved in data interpretation and manuscript revision. IF contributed in data acquisition and analysis as well as manuscript revision. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: 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.

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