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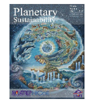

SUSTAINABLE ALTERNATIVE FEED FOR AQUACULTURE: STATE OF THE ART AND FUTURE PERSPECTIVE

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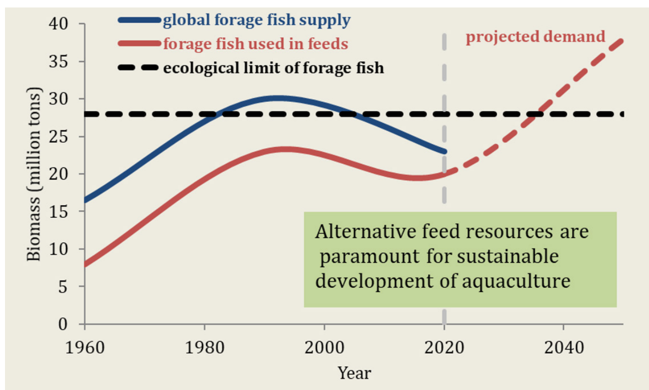
HIGHLIGHTS

- Fishery and aquaculture by-product inclusion in aquafeeds can enhance the growth, immunity, and flesh color of aquatic animals.
- The use of fishmeal and fish oil (FMFO) has been recognized as the leading unsustainable factor in aquaculture.
- Sustainably produced insect meals are rich in protein and are comparable to fishmeal in essential amino acids.
- Microalgae biomass can accumulate high levels of protein and lipids, along with several value-added components that benefit fish health and quality.
- 100% replacement of fishmeal with marine amphipod meal in the diet of juvenile marine fish did not cause any negative impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

With aquaculture intensifying to meet future demands and forage fish stocks nearing their ecological limits, fed aquaculture must continue to scale down reliance on fishmeal and fish oil to safeguard the sustainable development of the sector. Sustainable alternative feed ingredients for the production of aquafeeds are paramount. Apart from terrestrial plant-based and animal-based ingredients, fishery and aquaculture by-products and insects are presently the most viable alternative sources.

Food waste, seaweed, and microbial sources show promise; however, they are still limited due to cost, processing, and scalability issues. Low-trophic marine animals demonstrate immense potential as sustainable and adequately nutritious substitute ingredients for fishmeal and fish oil. Societal shifts in diets to non-fed aquaculture products and advancements in integrated multi-trophic aquaculture systems offer additional future avenues of interest. In this review, we explore the current list of sustainable ingredients that have demonstrated promise as a replacement for fishmeal and fish oil in aquafeeds.

List of Abbreviations

DDT	Dichlorodiphenyltrichloroethane
DHA	docosahexaenoic acid
DW	dry weight
EPA	eicosapentaenoic acid
e.g.	example
EU	European Union
F&A by-products	fishery and aquaculture by-products
FAO	Food and Agriculture Organization
FMFO	fishmeal and fish oilHUFA highly unsaturated fatty acid
i.e.	id est; that is
kg $^{-1}$	kilogram
m^2	square meter
PUFA	polyunsaturated fatty acid
SCO	single-cell organisms
SDG's	sustainable development goals
UN	United Nations
US$	United States Dollar
USA	United States of America

Sustainable Aquaculture

As the human population is predicted to reach 9.7 billion by the year 2050 (UN 2015), nutrient-rich food supplies are estimated to require a 25–75% increase in production to meet future demands (Hunter *et al*., 2017). Simultaneously, the rise of the "middle class" throughout Africa and Asia has created a shift in diets with a preference for animal-sourced proteins (Goodman & Robison, 2013; Tschirley *et al.*, 2015). Increased livestock production to support these demands has raised major environmental concerns around land conversion, overexploitation of grasslands, and greenhouse gas emissions (Michalk *et al.,* 2018). This has made aquaculture intervention an integral part of the future plan for increasing animal protein production and ensuring food security (Hua *et al.*, 2019; FAO, 2020). In fact, aquaculture is currently the fastest-growing food production sector over the last three decades (FAO, 2018), surpassing global beef production in 2012 (Larsen & Roney, 2013). Aquaculture offers many benefits such as poverty reduction in low-income countries (Filipski & Belton, 2018), increased production from new culture systems and genetic improvement technologies (Gratacap *et al*., 2019; Khanjani & Sharifinia, 2020; Azra *et al.*, 2022), and production of eco-friendly non-fed (e.g., silver carp), and waste/nutrient extractive species (e.g., seaweed; Poore & Nemecek, 2018; Chopin & Tacon, 2021).

In 2015, the United Nations announced 17 sustainable development goals (SDGs) as part of their 2030 development agenda to ensure peace and prosperity on Earth. As aquaculture rapidly expands, efforts toward achieving some of the UN's sustainable development goals have heightened, especially around the conservation of natural resources and reduction of waste by conversion of such to feed finfish and crustaceans (Tacon & Metian, 2015). Sustainable development is defined as the "use of the environment and resources to meet the needs of the present without compromising the ability of future generations to meet their own needs"; hence, it is built on 'three pillars' namely, social, economic, and environmental sustainability (World Commission on Environment and Development, 1987). Therefore, the aim of sustainable aquaculture is to find a balance between all three pillars, in which farmed aquatic nutrients can be provided for human consumption without harming ecosystems or exhausting natural resources (Boyd *et al.*, 2020). However, oftentimes, interests within the pillars are not aligned, causing imbalances that hinder sustainability.

Several factors negatively impact aquaculture sustainability. Environmentally, issues around degradation, conversion, and pollution of aquatic and terrestrial habitats persist along with concerns over the exploitation of limited natural resources (Boyd *et al.*, 2020). Whereas social and economic sustainability are challenged by public perception, policy, inequity, production costs, diseases, and supply chain issues (Peñalosa Martinell *et al.*, 2020). Some experts suggest that the expansion of sustainable aquaculture alone is potentially sufficient to meet the future's food demands (Costello *et al.*, 2020). While others argue that marine aquaculture will continue to face limitations and perhaps even undermine future food security and environmental sustainability (Belton *et al.*, 2020). Recent technological advancements such as artificial intelligence and cloud computing are being employed to improve traceability, feeding, disease detection, and environmental monitoring (Mustapha *et al.*, 2021) while new innovative, multi-faceted frameworks are being developed (i.e., One Health lens) to improve sustainable aquaculture practices worldwide through integration, evidence, policy, and legislation (Stentiford *et al.*, 2020). This review, therefore, explores the current state and future perspective of sustainable aquaculture feed production.

Aquaculture Feed

Aquaculture produces "fed" (e.g., shrimp, sea bass, salmon) and "non-fed" (e.g., silver carp, seaweed, oyster) species (Figure 1 and Figure 2). Traditionally, fed aquaculture relies heavily on aquafeeds composed of high concentrations of fishmeal and fish oil (FMFO) derived from wild-caught forage fish to provide protein, essential fatty acids, micronutrients, and improved palatability (Froehlich *et al.*, 2018). The use of FMFO has been recognized as the leading unsustainable factor in aquaculture (Ghamkhar & Hicks, 2020). It adds to the pressure on dwindling wild fish stocks and disrupts the balance of aquatic food webs (Hua *et al.*, 2019). In fact, around 68% of the total global aquaculture production of fish and crustaceans are direct-fed species (Tacon, 2020). Hence, the total production of aquafeeds is projected to increase by 75%, from 49.7 million tons in 2015 to 87.1 million tons by 2025 (Tacon & Metian, 2015). Some estimates have demonstrated the fact that at the current rate of development, fed aquaculture will eventually exceed the ecological supply of forage fish (Froehlich *et al.*, 2018).

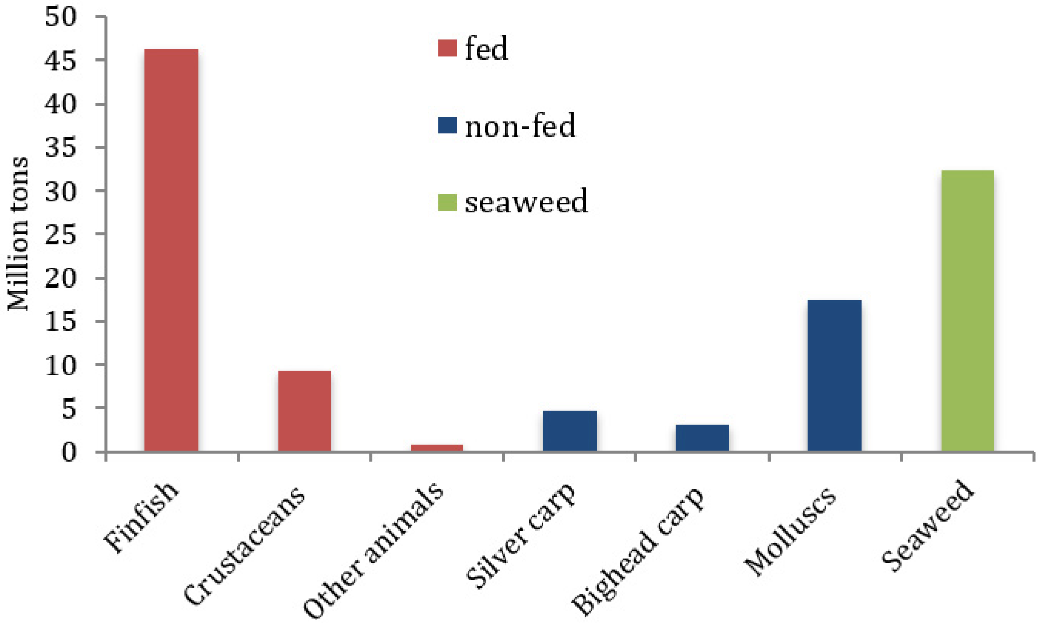

Figure 1: Total aquaculture production values in 2018 of fed and non-fed fish, including seaweed. Adapted from data released in the FAO (2020) report

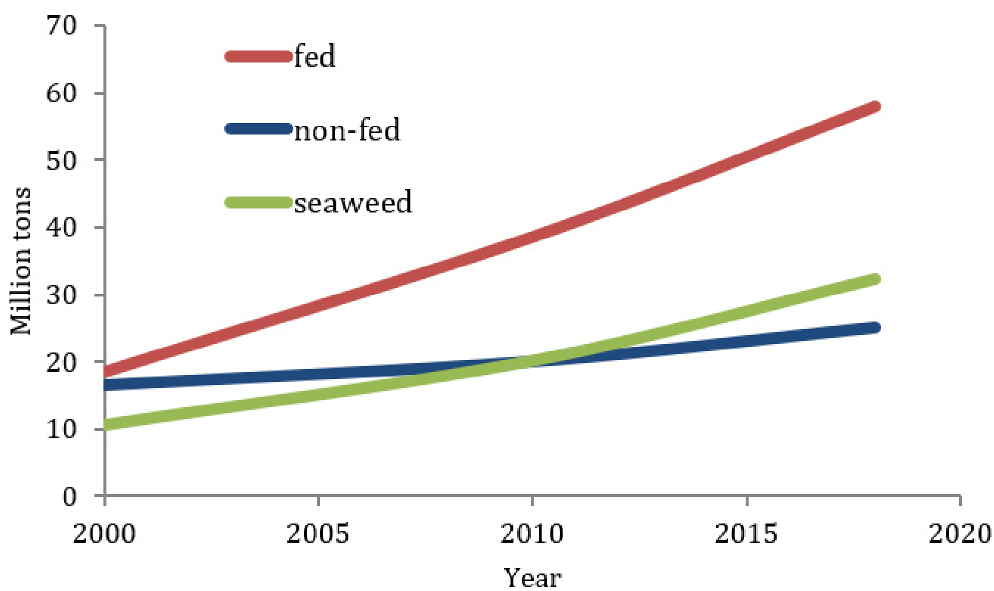

Figure 2: Historic growth of fed and non-fed total aquaculture production values, including seaweed. Adapted from data released in the FAO (2020) report

Another problem with wild-sourced fishmeal is the accumulation of heavy metals, chemicals, and microplastics in marine fish because of urbanization and industrialization activities (Hanachi *et al.*, 2019). Nevertheless, around 12% of the total wild-caught fishery goes towards feeding high-value fish and crustaceans (FAO, 2018) to sustain an average annual production growth rate of 5.70% (fish) and 9.91% (crustaceans) since 2000 (FAO, 2019). Economic incentives drive this growth in which high-value fed species are cultured in developing countries and exported internationally to more affluent countries (Hua *et al.*, 2019). Although fed aquaculture's reliance on current aquafeeds is detrimental to environmental sustainability, fed aquaculture has been shown to contribute to poverty alleviation and food security in underdeveloped nations where the majority of productions takes place (Silva & Davy, 2010; Belton *et al.*, 2018; Hoover *et al.*, 2019). Nevertheless, finding the proper balance between the production of high-value fed species and low-input unfed species is key for aquaculture development to play an important role in providing food security and economic relief in the future.

Typically, feed accounts for 40−80% of aquaculture production costs (Rana *et al.*, 2009; Ayadi *et al.*, 2012; Okomoda *et al.*, 2020). This cost continues to rise due to several factors (e.g., cereal crop shortages, oil prices, global warming, and demand), impacting the more vulnerable small-scale producers and rural farmers the most (Rana *et al.*, 2009). In fact, FMFO prices are expected to increase up to 13% by 2030 due to global demand (FAO, 2020). As aquaculture continues to grow, the dependency on FMFO has been recognized as the leading challenge to achieving sustainability within the sector (Tacon *et al.*, 2022). Due to the environmental impact and limitations of forage fish-sourced meals along with rising costs, various raw materials have been adopted in order to reduce FMFO inclusion in aquafeeds. Currently, numerous plant-based products such as soybean meal and rapeseed meal, as well as animal-based by-products, like bone meal and poultry meal, are being used as alternative protein sources in aquafeeds. However, these sources come with considerable limitations and only add to the mounting pressure already surrounding land-based agriculture systems.

Plant-based products often contain anti-nutritional elements and high proportions of fiber that can negatively impact growth performance, health, and nutrient digestibility in aquaculture species (Okomoda *et al.,* 2020). In addition, they are deficient in long-chain polyunsaturated fatty acids (PUFAs) and micronutrients essential to the health and development of most aquaculture products, especially at the larval and nursery rearing stages (Malcorps *et al.,* 2019). The necessity to identify alternative sustainable, healthy, and cost-effective ingredients for use in aquafeed formulations cannot be overemphasized. The search for alternative sources able to replace fish-derived sources and potentially minimize the disadvantages related to vegetable protein sources, even at low inclusion rates is a top priority (Cottrell *et al.*, 2020). Such ingredients must be effective to enhance growth, feed efficiency, and fish health while being environmentally, socially, and economically sustainable when mass-produced.

Fishery and Aquaculture By-products

The term fish wastes are used to describe different categories of unwanted food fish, such as small-sized fish species, by-catches, as well as the by-products of fisheries and aquaculture industries (Olsen *et al.*, 2014). These are either products with less market value or waste from processing that are not routinely eaten (e.g., head, skin, fins and viscera carapax, exoskeleton, shell, debris, etc.) and can constitute more than 50% of the fish's body (Gasco *et al.*, 2020). In 2014, the FAO estimated the global waste from the aquaculture and fisheries sector to exceed 20 million tons, with the marine fishery catch alone constituting about 25% of the total value (FAOSTAT, 2014; Caruso, 2016). In the European Union (EU), the total discard was estimated to be 5.2 million tons per year (Olsen *et al.*, 2014; Lopes *et al.,* 2015). This led to the enactment of the landing obligation [Reg. (EU) No. 1380/2013; European Commission, 2013] law which was targeted to reduce the level of unwanted catches in the EU (Guillen *et al.*, 2018). However, as the quest to improve food production through aquaculture increases and the efforts to export fish fillet to other countries intensifies, fish processing would increase, leading to large amounts of solid waste generated from filleting and shell removal from shrimps and shellfish (Gamarro *et al.*, 2013; Secci *et al.*, 2016). The disposal of the fish waste generated is usually the major problem in many countries as the environmental impact of inappropriate disposal could have a significant effect on the aquatic ecosystems (Arvanitoyannis & Kassaveti, 2008). This includes the release of organic wastes, which might significantly alter the microbiota structure and the biodiversity of the benthic assemblages in the aquatic ecosystem (Olsen *et al.*, 2014). Therefore, the need for proper management of fish waste and by-products cannot be overemphasized to abate pollution problems that may emanate from indiscriminate disposal.

One such way of management of these unwanted products is their inclusion in the feed formulated for animals and aquaculture species (EU, 2003; Ferraro *et al.*, 2010). According to the EU Regulation 1069/2009, the fish and aquaculture by-products are part of the Category 3 by-products that are allowable for inclusion in animal diets to contribute responsibly to the environment and public health (Gasco *et al.*, 2020). Discarded fishery by-products can be used in the production of FMFO (Li *et al.*, 2019). Consequently, this could significantly reduce the pressure on conventional fish stocks used in the production of fishmeal, hence, constituting a more sustainable approach to fish farming (Garcıa-Romero *et al.*, 2014; Kim *et al.*, 2014; Gisbert *et al.*, 2018). The economic benefit of reducing the cost of feed formulation, production, and administration is thereby occasioned by the eco-friendly approach to obtaining high-valued nutrient matter from materials considered waste (Li *et al.*, 2019). Enzymatic hydrolysis of the fisheries discards is another technique of processing the waste to fish protein hydrolysates which are simply short-chain peptides and amino acids (Gasco *et al.,* 2020). Therefore, the advantage of the inclusion of fishery and aquaculture by-products (F&A by-products) in the formulated diet of fish is in its rich macro and micronutrients (Olsen *et al.*, 2014; Elhag *et al.*, 2022). Some studies have demonstrated the beneficial biological effects of feeding F&A by-products, including improving the growth, immune system (Kotzamanis *et al.*, 2007), and antioxidant activity of the fed fish (Ambigaipalan & Shahidi, 2017). They also serve to enhance the fish's flesh color as well as sensory properties when used as feed additives in red porgy, Pagrus pagrus, crab, and yellow croaker, Larimichthys croceus (Garcıa-Romero *et al.*, 2014; Yi *et al.*, 2015).

However, due to the variability in the proportion of parts that makes up the composition of the F&A by-products, the nutritional components could have a wide range in terms of protein and essential amino acid values (Pinotti *et al.*, 2016; Villamil *et al.*, 2017). In addition, the various technology adopted for the processing of different kinds of by-products can significantly impact the amino acid profile, thereby causing a reduction (i.e., between 42–90%) in nutrients (Gehring *et al.*, 2011). Also, the hygienic condition of the stored products especially discards in liquid form (i.e., silage), is a source of concern as they present an avenue for infection and food poisoning in the aquaculture facility (Guillen *et al.*, 2018). Iriondo-DeHond *et al.* (2019) also highlighted the possibility of the by-products affecting the quality of fish produced by way of easy oxidation, offensive odor, and alterations of the market value based on the negative perception of the consumer about the nutritional value and fish health status. One of the major problems of the by-product processing industry is its short shelf life, both in the liquid and solid state; hence, logistics for the management of this high perishability product may be very capital intensive (Ween *et al.*, 2017). However, unusable F&A by-products (i.e., decomposing) alternatively can be used for the rearing of insects, which is also usable in the formulation of fish feed, as detailed in subsequent sections herein (Liland *et al.*, 2017). It is also important to state that the use of these by-products is not permissive in the EU for growing insects meant to be used as food for humans or animal feed (Pinotti *et al.*, 2019). Another cause of worry is the ban enforced by the EU [Reg. (EC) No. 1069/2009; European Commission, 2009] which prevents the feeding of F&A by-products to the same aquaculture species (Gasco *et al.,* 2020). Many studies on the extraction of valuable bioactive chemicals of pharmaceutical, nutraceutical, and cosmeceutical importance have been reported (Najafian & Babji, 2012; Ahn *et al.*, 2015; Chi *et al*., 2015; Nurdiani *et al.*, 2017; Pangestuti & Kim, 2017). Therefore, the growing interest of several companies in F&A by-products for the isolation of anti-inflammatory, immunomodulatory, antimicrobial, antiviral, anti-carcinogenic, antioxidant, and cardioprotective substances (Cheung *et al.*, 2015; Shabani *et al.*, 2018; Bruno *et al.*, 2019) may constitute competitive interest against their use in aquafeed.

Food Wastes

Food wastes are another nontraditional protein source that can be used in the production of aquafeed (Bake *et al.*, 2009; Nasser *et al.*, 2018). It includes discarded raw and cooked food substances or those intended to be discarded, as well as recycled food leftovers (USEPA, 2012; Cheng *et al.*, 2015; Choi *et al.*, 2016). FAO (2015) had earlier estimated that 1.3 billion tons of food produced for human consumption is discarded as waste. That loss constitutes about one-third of the total global food production, yet, an estimated 925 million people are living in starvation in low-income and developing countries (Buckle, 2015). Unconsumed foods usually end up in a landfill, which decomposes, producing landfill leachates and gases such as methane (Ishigaki *et al.*, 2002). The methane produced is a greenhouse gas that is detrimental to the environment because it has 20 times the effect of carbon dioxide considering its global warming potential (Bake *et al.*, 2009; FAO, 2015). Incineration of waste is another method used in handling food waste. However, the environmental pollution of the combustion process coupled with the inefficiency of combustion due to the high moisture content of the waste discarded has discouraged the use of the incineration method (Xiao *et al.*, 2007; Zhuang *et al.*, 2008). Food wastes are also recycled to produce biofuel and fertilizer. Nevertheless, the low capacity of such recycling industries, coupled with the availability of alternative raw materials that are stable, clean, and have a longer shelf life is a limitation (HKEPD, 2012). Therefore, there is a need to adopt novel methods for the utilization of these neglected and inexpensive sources of high-nutrient protein that go to waste.

Food wastes are a valuable resource that can be used in diets formulated for aquaculture species, thereby substantially reducing the inclusion of expensive feed ingredients (Cheng *et al.*, 2014; Wong *et al.*, 2016). Generally, food waste from restaurants and household leftovers meant for human consumption are also suitable for omnivorous aquaculture candidates such as tilapia (Nasser *et al.*, 2018). Several previous studies have demonstrated the potential use of food waste in aquafeed. For instance, the study by Hsieh (2010) revealed that the orange-spotted grouper Epinephelus coioides could tolerate 10–20% of food waste emanating from a university cafeteria without significantly affecting growth performance. Similar findings have been reported by Al-Ruqaie (2007) and Bake *et al*. (2013) on Nile tilapia fed food leftovers compared to those fed only commercial diets. The nutritional analysis of Mo *et al.* (2014) revealed satisfactory levels of nutrients such as proteins, essential amino acids, carbohydrates, fats, and phosphates in food waste. These nutrients are sufficient for culturing aquaculture fish species such as grass carp, grey mullet, bighead carp, and tilapia, otherwise known as low-trophic level species. Interestingly, the reports of Cheng *et al.* (2014; 2015) had also shown that fish-fed food waste-based pellets are safer for consumption than those fed commercial feed pellets because of low levels of bio-accumulated contaminants such as DDT (Dichlorodiphenyltrichloroethane) and mercury. However, the studies referenced above used sorted food waste from specific sources; therefore, their nutritional composition is not unified, unlike the heterogeneous nature of conventional wastes from different sources.

Depending on the source and composition of the food waste, the possibility of high variation in nutritional parameters of conventional waste suggests they will not provide adequate nutrients for fish (Castrica *et al.*, 2018; Nasser *et al.*, 2018; Georganas *et al.*, 2020; ZeinEddine *et al.*, 2021). Sorting into classes could checkmate this problem; however, the process could be very cumbersome, especially when it is not automated. Therefore, improvement in the utilization potential will depend on the successful manipulation of the nutritional quality of the food waste using options such as bioprocessing or fermentation (Hassaan *et al.*, 2018). This involves the biotransformation of leftovers using microorganisms to improve nutritional contents such as crude protein and consequently reducing the crude fiber content of the waste (Van De Lagemaat & Pyle, 2001). Food waste has also been demonstrated to be an alternative source of nutrients for the culture of microalgae which in turn can be used in fish hatcheries as feed for larvae or as enrichment for aquaculture live food like Artemia and rotifers (Muller-Feuga, 2000). The conventional methods of microalgal cultures are costly and could represent about 30% of a hatchery's operating cost (Coutteau & Sorgeloos, 1992). Hence, the utilization of food waste as an alternative to the expensive culture medium help lower aquaculture seed production cost (Pleissner *et al.*, 2013). Another alternative to the use of food waste that is unfit for animal consumption is to convert them to substrates for the rearing of insects, which in turn can be used for fish feed formulation (Liland *et al.*, 2017).

Just as stated earlier for F&A by-products, the EU does not permit the use of food waste for food fish or growing insects as part of their 'precautionary' principle applied to the food safety policy (Sogari *et al.*, 2019; Fowles & Nansen, 2020). The ban on food waste usage in animal feed can be traced to the 2002 outbreak of foot-and-mouth disease in the United Kingdom (Zu Ermgassen *et al.,* 2016). Therefore, to prevent the future spread of prion diseases, the EU placed a ban on the use of processed animal protein, food waste, and other poor substrates in the diet of animals (Karapanagiotidis, 2014). In the same vein, countries such as Australia, New Zealand, Canada, and the USA have strict regulations on the material usable in animal feeding (Westendorf, 2000). However, this is not the same narrative in other parts of the world where fewer restrictions are placed on the direct or indirect use of poor substrates such as food wastes in animal feed, thereby ensuring the realization of the circular economy and zero waste concept (Pinotti *et al.*, 2019; Sogari *et al.*, 2019). Also, the development of organic waste treatment facilities with the capacity to convert food waste to compost, fertilizers, and biogas utilizing aerobic and anaerobic decomposition processing could constitute a potential competitive use. However, with automated sorting, good quality material can be separated for aquafeed production while the other unfit food waste is directed for organic waste transformation to useful chemicals.

Insects

Insect-based feed materials are arguably the most important topic of interest regarding aquaculture nutrition (Barroso *et al.,* 2014; Henry *et al.,* 2015; Nogales-Mérida *et al.,* 2019). For the past two decades, investigations on insect meals as alternative sources for fishmeal and soybean meal have been ongoing. Results of the complete replacement of these conventional feed ingredients in the diet of different aquaculture species have been promising (Nogales-Mérida *et al.,* 2019; Xu *et al.,* 2020; Alfiko *et al.,* 2022). These studies have included meals made from different stages of development of the insect, such as larva, pupa, and adult (Karthic *et al.,* 2019; Sogari *et al.,* 2019; Van Huis, 2020; Hawkey *et al.,* 2021). In recent times, the European Commission approved the inclusion of insects in the diets of aquatic organisms (Regulation 2017/893/EC, 2017). This singular act has given the necessary boost to the nutritional industry on its use as an important feed ingredient (Weththasinghe *et al.,* 2021). Since then, significant investments in insect-rearing start-up enterprises have been witnessed all around the world, with not less than 42 European enterprises established and actively involved in the production of different kinds of insects at the beginning of 2019 alone (Mancuso *et al.,* 2019). The global insect production at that time was estimated at 50,000 tons per year, with the presumption of an increase soon (IPIFF, 2019; Mancuso *et al.,* 2019).

Out of almost a million recognized insect species worldwide, not less than 16 insect species have been evaluated as an alternative protein source for aquaculture species (Henry *et al.,* 2015; Nogales-Mérida *et al.,* 2019; Guerreiro *et al.,* 2020). According to Alfiko *et al.* (2022), only eight species from these studies have been scientifically reported to show promising results. They include silkworm *Bombyx mori* (Ji *et al.,* 2015; Nuswantoro & Rahardjo, 2018; Wu *et al.,* 2021), black soldier fly *Hermetia illucens* (Katya *et al.,* 2017; Dumas *et al.,* 2018; Zarantoniello *et al.,* 2019), housefly maggot and pupae *Musca domestica* (Emeka & Oscar, 2016; Kolawole & Ugwumba, 2018; Achionye-Nzeh & Ngwudo, 2021), mealworms (i.e., yellow mealworms *Tenebrio molitor* and lesser mealworm *Alphitobius diaperinus*) (Yi *et al.,* 2013; Su *et al.,* 2017; Rumbos *et al.,* 2019; Jeong *et al.,* 2020; Basto *et al.,* 2021; Kureˇcka *et al.,* 2021) and cricket (which includes house cricket *Acheta domesticus,* banded cricket *Gryllodes sigillatus* and Jamaican field cricket *Gryllus assimilis*) (Vandeweyer *et al.,* 2018; Nikoletta, 2019; Hessler Frelinckx, 2019; Jo ́zefiak *et al.,* 2019; Tilami *et al.,* 2020; Masson *et al.,* 2020; Yue & Shen, 2021). These insect species are reported to have high crude protein ranging from 42−60% (Figure 3) and are comparable to fishmeal as well as soybean meal in essential amino acids (Henry *et al.,* 2015; Allegretti *et al.,* 2017).

The consideration of insect-based feed resources as potential alternatives to expensive conventional ingredients is not only based on its comparable nutritional component to the latter but on several other observable advantages (Barroso *et al.,* 2014; Henry *et al.,* 2015; Nogales-Mérida *et al.,* 2019). This includes a reduced environmental impact as regards production and processing as well as possibilities of conversion of waste to wealth as they thrive well on wastes and by-products with high conversion efficiency (Zarantoniello *et al.,* 2018). In addition, there is a reduced risk of zoonotic infections as they are non-pathogenic, non-vectors of pathogens, and non-invasive species of insects (Hua, 2021). Also, they do not contain antinutrients that can hamper feed utilization when fed to animals (Sealey *et al.,* 2011; Van *et al.,* 2013; Spranghers *et al.,* 2017). Aside from their proven ability to facilitate and enhance the growth as well as the welfare of aquaculture species upon feeding, this feed resource could be a sustainable option as it has the potential for mass culture (Stamer *et al.,* 2014; Zarantoniello *et al.,* 2019; Alfiko *et al.,* 2022). Although the risk assessments of insect-based feeds have been evaluated critically and given a positive scientific review, there is a court of public opinion with neophobia syndrome and a negative perception of the use of insects in food fish (Sánchez-Muros *et al.,* 2014; Henry *et al.,* 2015; Schlüter *et al.,* 2016).

Although humans have long been using insects as a source of food in various countries, many people in developed countries find it disgusting to eat insects or fish and shellfish raised with an insect-based diet (Daniel, 2018; Wu *et al.,* 2021). However, that does not invalidate the fact that insects constitute a significant portion of the food of many in poor and low-income countries, hence, constituting competitive interest. In addition, important bioactive peptides have been isolated from some insects (e.g., silkworm pupae) and used in the industry as a source of high-value proteins and bioactive peptides (Altomare *et al.,* 2020). Consequently, the price of dried silkworm pupa is much higher than fishmeal in the global market, costing as much as US$ 3,500/ton compared to US$ 1,505/ton for fishmeal as of June 2021 (Alfiko *et al.,* 2022). Therefore, the use of such insect options for human consumption or animal nutrition would not be economically viable when compared to the use of conventional feed ingredients (i.e., fishmeal and soybean meal). Another disadvantage to insect-based feed production is that it is labor intensive as insect farming is yet to be automated (Alfiko *et al.,* 2022). Continuous use of manual labor has implications on production costs as well as production efficiency. Hence, to improve the yield and profitability of insect-based feed production, novel technologies (i.e., genome editing) and automation (i.e., internet of things) would need to be employed in the future (Yue & Shen, 2021). Importantly, approval for the use of insect-based meals in aquafeeds by the governments of different countries must be matched with massive sensitization of the consumers about the safety and benefits of its use in food fish.

Research on the sustainable substrate to produce insects must be intensified. One of which is food waste that is unfit for human or animal consumption. Unfortunately, the 'precautionary' principle of the EU has placed a ban on the use of substrates such as catering and animal wastes to produce insects (Pinotti *et al.,* 2019; Sogari *et al.,* 2019; Fowles & Nansen, 2020). These kinds of food safety policies can hamper the growth of the insect-based feed industries as it limits the use of potential low-cost substrate in realizing the concept of a circular economy and zero waste. Although it has been stated earlier that there is no evidence of zoonotic infections as a result of people consuming the fish raised on an insect-based diet, however, the workers in the insect production sector may be at risk of infection. This may be due to allergies developed from their contact, inhalation, and sighting of the messy environment of production spaces (Macombe *et al.,* 2019). Importantly, the insect may not be a carrying vector for pathogens; however, production at such high densities under limited space can cause an outbreak of infections and diseases from bacteria, viruses, and fungi (EFSA, 2015). This, therefore, can constitute an avenue for severe economic losses as production is crashed due to an infection outbreak (Gasco *et al.,* 2020). It is therefore important to have adequate knowledge of possible insect disease outbreaks and control as well as engage in good farming practices that maintain environmental hygiene and include proper Hazard Analysis and Critical Control Points plans before initiating an insect-based production factory (Gasco *et al.,* 2020).

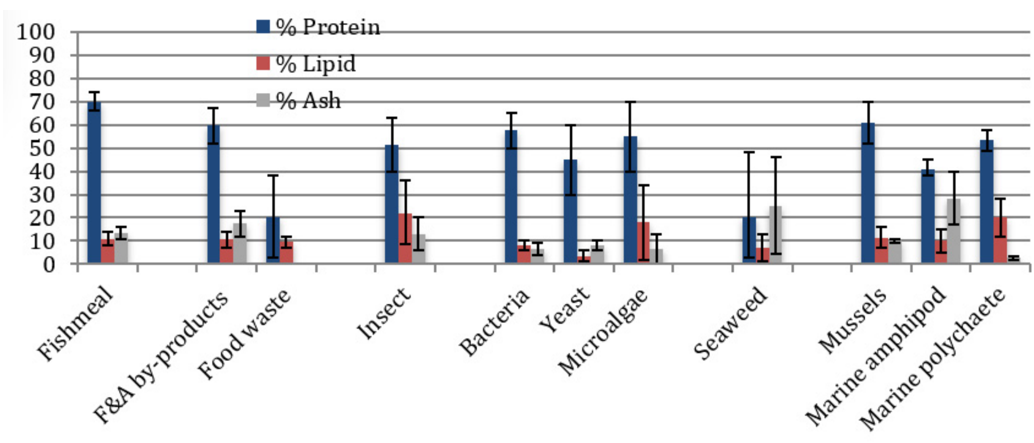

Figure 3: Summary of crude protein, crude lipid, and ash proximate composition (% dry weight) ranges previously reported. The bars shown express the midrange value calculated for each variable. Error bars indicate the upper and lower limit of the ranges reported
(Derived from Baeza-Rojano *et al.*, 2014; Hua *et al.*, 2019; Glencross *et al.*, 2020; Jusadi *et al.*, 2021; Nagappan *et al.*, 2021; Selvam, 2021; Albrektsen *et al.*, 2022; Mohan *et al.*, 2022)

Single-cell Organisms

Single-cell organisms (SCO) of various types, such as bacteria, fungi, microalgae, and combinations thereof (e.g., biofloc), have proven to be a good substitute for FMFO in terms of nutritional composition and feed effectiveness. In fact, the inclusion of SCO in feed has led to enhancements in growth performance, immunity, health, and quality of fish (Shah *et al.,* 2018; Richard *et al.*, 2021). Production of SCO is deemed sustainable, as they are fast growers, use very little fresh water, and do not require any agricultural land for propagation. Also, they can be produced from non-food waste streams and aquaculture wastes (Viegas *et al.*, 2021; Albrektsen *et al.*, 2022).

Bacteria have the advantage of rapid growth on organic substrates, such as methane, methanol, syngas, carbon dioxide, hydrogen, and second-generation sugars (Matassa *et al*., 2020). Gas-based fermentation technology uses natural gas as a carbon and energy source to produce methanotrophic bacteria meal. Natural gas resources are plentiful and low-cost, making protein production from natural gas a reasonable large-scale alternative. A bacterial meal has up to 80% crude protein (mean = 60%) and around 10% fat, which is comparable to fishmeal (Glencross *et al.*, 2020; Albrektsen *et al*., 2022). Previous studies have shown that salmon and trout-fed diets with up to 55% and 38%, respectively, methanotrophic bacterial meal (i.e., Methylococcus capsulatus, Methylobacterium extorquens) displayed either increased growth performance and feed efficiency or no adverse growth effects (Aas *et al.*, 2006; Øverland *et al.,* 2010; Hardy *et al.*, 2018). However, long-term feeding with high concentrations of bacterial meal inclusion lead to decreased protein digestibility as well as reduced growth and survival of salmon (Storebakken *et al*., 2004).

Recent advancements in gas-based fermentation technology are taking place, and several commercial methanotroph-based bacterial meals are expected to be available in the near future (Albrektsen *et al.*, 2022). Shrimp have responded well to various bacterial meals, with inclusion rates ranging from 10% to complete replacement of fishmeal in shrimp diets (Tlusty *et al.*, 2017; Hamidoghli *et al.*, 2019). Recently, the inclusion of an emerging new microbial protein source, photoheterotrophic grown purple non-sulfur bacteria (i.e., Rhodopseudomonas palustris and Rhodobacter capsulatus) enhanced growth performance, feed conversion ratio, and resistance to disease and stress in shrimp (Alloul *et al.*, 2021). Also, these purple phototrophic bacteria produced using wastewater replaced up to 66% fishmeal in diets of sea bass without any adverse effects on fish performance (Delamare-Deboutteville *et al.*, 2019).

Yeasts have also gained attention as an alternative feed resource that is high in crude protein ranging from 30−60% (mean = 45%) (Glencross *et al.*, 2020). They can be produced using non-food biomass from forestry, agriculture, and organic waste streams, with limited land and water use requirements. Like bacteria, yeast meals (mostly Saccharomyces cerevisiae) have shown promising results when partially replacing fishmeal, mostly in diets of salmonids, along with beneficial immunostimulant activity. However, high inclusion rates indicated reductions in growth performance and digestibility (Vidakovic *et al.,* 2020; Hansen *et al*., 2021). Similar trends from a few studies were observed for shrimp (Xiong *et al.*, 2018; Nguyen *et al.*, 2019), tilapia (Al-Hafedh & Alam, 2013), and marine fish (i.e., sea bass, sea bream) (Oliva-Teles & Gonçalves, 2001; Oliva-Teles *et al.*, 2006) being fed yeast meals. Although bacteria and yeast demonstrate high potential as an alternative to fishmeal, their use is still limited by high processing costs and relatively low production capability (Delamare-Deboutteville *et al*., 2019). Additionally, studies on the improvement of nutrient digestibility and palatability of bacteria and yeast-based feeds are needed.

Microalgae have a high potential to become a legitimate, sustainable replacement for FMFO in aquafeeds. They can be produced using seawater or wastewater on arid, unfertile land with minimal nutrients (Viegas *et al.*, 2021; Ahmad *et al.*, 2022) whilst maintaining a net biomass production that is higher than any terrestrial plant or animal (Rizwan *et al.*, 2018). Microalgae biomass can accumulate high levels of protein and lipids that are suitable for fish growth and development. Typically, crude protein content in microalgae ranges from 40−70% (Nagappan *et al.*, 2021). Also, they contain many value-added components such as carbohydrates, vitamins, antioxidants, probiotics, carotenoids, and amino acids that benefit fish health and quality (Chen *et al.*, 2021). Furthermore, various species produce high levels of essential omega-3 fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) that can account for 30−50% of their total fatty acid content (Albrektsen *et al.*, 2022). Several omega-3 PUFA and long-chain highly unsaturated fatty acid (HUFA) rich microalgae were found to be a suitable substitute for lipids and fish oil in feed (Cottrell *et al.*, 2020).

Omega-3 fatty acids provide health benefits not only to fish but also to humans (Ryckebosch *et al.*, 2012). For instance, Nannochloropsis sp. contains about 30–40% of omega-3 fatty acids in their total content (Adarme-Vega *et al.,* 2012). In addition, microalgae yields can be significantly enhanced for PUFA, protein, lipid, pigment content, etc., by modifying culture conditions (e.g., light intensity, nutrients, and temperature) (Glencross *et al.*, 2020). Recently, a combination of two microalgae species, Nannochloropsis oculata and Schizochytrium sp., was tested as a total replacement for FMFO in the diet Nile tilapia, Oreochromis niloticus and resulted in higher growth performance, nutritional quality, and nutrient digestibility in tilapia (Sarker *et al*., 2020a). Also, a combination of Nannochloropsis sp. and Isochrysis sp. was tested as a replacement for FMFO in the diet of rainbow trout, Oncorhynchus mykiss, and was found to significantly increase digestibility for crude proteins, amino acids, lipids, and fatty acids (Sarker *et al.,* 2020b). Microalgae meal production is deemed sustainable due to its circular model. The carbon used to accumulate microalgal biomass is eventually digested and expelled as waste. Thereafter, subsequent treatment of aquaculture effluents will release the carbon back into the atmosphere as carbon dioxide, closing the circle (Chen *et al.,* 2021).

Although microalgae-based feeds are a promising alternative to traditional aquafeeds, several problems still persist. Safety hazards are present due to the ability of microalgae to adsorb and accumulate heavy metals (Pavithra *et al.*, 2020). The build-up of these hazardous elements could eventually threaten the health of people consuming aquaculture products fed microalgae-based aquafeeds. Also, a few studies have reported the presence of anti-nutritional factors in microalgae, such as lectins and tanic acid (Wu *et al.,* 2005; Silva *et al.,* 2021). Poor digestibility of microalgae, mainly due to a cellulose-rich cell wall and high portions of starch found within the cell, has been a reoccurring issue (Ahmad *et al.,* 2020). For both anti-nutritional factors and poor digestibility, specification, and quantification are required, followed by advancement in reduction and pre-treatment technology (Olukomaiya *et al.,* 2020). Finally, the high cost of microalgae production continues to be a barrier to achieving mass adoption as an FMFO replacement. Unfortunately, processing costs associated with microalgae biomass collection and drying are still excessive (Fasaei *et al.,* 2018).

Seaweed

Global seaweed (i.e., macroalgae) aquaculture production was 32 million tons in 2018, accounting for 51% of global mariculture production, valued at over USD 11 billion (FAO, 2020). Currently, over 99% of seaweed cultivation takes place in Asia, with a growing percentage coming from Africa (FAO, 2020). The majority (≈ 95%) of seaweed produced (e.g., Japanese kelp, Japanese wakame) is for human consumption (Ferdouse *et al.,* 2018). Recently, seaweed has been highlighted for its bioremediation capability that enables a highly sustainable production scenario. Seaweed cultivation is integrated into existing sources of nutrient-rich wastewater from various sources (e.g., agriculture, aquaculture, power generation), thus, utilizing and converting those nutrients to biomass while reducing environmental impact (Ge *et al.,* 2017; Neveux et al., 2018; Arumugam *et al.*, 2019). Seaweed nutrient content can vary considerably depending on the taxonomic group (i.e., red, green, brown) and seasonality (Wan *et al.*, 2019). Protein content ranges are 6−38% (red), 3−35% (green), and 2−17% (brown), whereas lipid ranges are <1−13% (red), <1−3% (green) and <1−10% (brown) (Wan *et al.*, 2019 as referenced in Nagappan *et al.*, 2021).

Although protein and lipid proportions in seaweed are modest compared to SCOs, they are, however, considered high-quality sources. The majority of species have protein that is rich in essential amino acids, with proportions of total amino acids exceeding those found in terrestrial plants and fishmeal (Cole *et al.,* 2015; Angell *et al.,* 2016). Also, numerous seaweed species contain high proportions of essential omega-3 HUFAs and PUFAs, such as EPA, stearidonic acid, a-linolenic acid, and arachidonic acid (Miyashita *et al.*, 2013). The carbohydrate content is usually the largest component, ranging from 15−65% of the total content of seaweed across the taxonomic groups (Wan *et al.*, 2019, as referenced in Nagappan *et al.*, 2021). Seaweed carbohydrates are high in dietary fiber (i.e., polysaccharides), ranging anywhere from 25−75% of the total content dry weight (DW). Although dietary fiber has several health benefits (e.g., prebiotic, anti-oxidant, anti-inflammatory), it is not easily digested by aquatic animals, especially carnivorous species.

Low-level inclusions of seaweed as a functional feed additive can provide several health benefits, such as enhanced immunity and improved resistance to stress of commercially important fish and shrimp (Yin *et al.*, 2014; Niu *et al.*, 2018; Øverland *et al.*, 2019). In general, as a fishmeal replacement, low inclusion rates (<10%) of whole seaweed in fish diets have shown enhancements in growth performance and pigmentation of commercial fish (Soler-Vila *et al.*, 2009; Wassef *et al.*, 2013; Ragaza *et al.*, 2021). Whereas inclusion rates above 10% tend to have negative effects on growth performance and nutrient digestibility (Abdel-Warith *et al.,* 2016; Qiu *et al.*, 2018). However, utilization as a viable FMFO replacement for some omnivorous and herbivorous species has been promising (Vucko *et al.*, 2017; Anh *et al.,* 2018; Manikandan *et al.,* 2022). For seaweed to replace fishmeal as an alternative source, it requires bio-refinement to isolate and enrich the protein content for use in meals.

Recently, enrichment processes have successfully doubled the biomass protein content of green, brown and red seaweeds while also producing some functional by-products (e.g., salt, ulvan, fucoidan, laminarin, carrageenan, phenolics, carotenoids) (Holdt & Kraan, 2011; Magnusson *et al.*, 2019; Øverland *et al.*, 2019; Gordalina *et al.,* 2021; Aasen *et al.,* 2022). Also, fermentation is another promising bio-refinement process for seaweed. Fermentation has been shown to triple in vitro digestibility, significantly increase protein and produce beneficial by-products such as organic acids, antioxidants, phenolics, and flavonoids (Fleurence *et al.,* 2018; Ang *et al.,* 2021). However, these processes are still being developed and currently require intensive downstream processing. Furthermore, under the current EU (EU Regulation 68/2013, EU, 2013a) and Canadian (Canada Justice Laws 2018) regulations, only seaweed biomass produced from drying and milling is permitted for use as a feed ingredient without special approval, warranting attention for advancing legislation. More research and innovation are required to advance the bio-refinement of seaweed to enable efficient and cost-effective production of biomass suitable for use as a fishmeal replacement (Bleakley & Hayes, 2017; Gordalina *et al.*, 2021).

Low-trophic Marine Animals

Marine animals of special interest for their potential utilization as FMFO replacements include mussels, amphipods, and polychaetes. These low-trophic organisms obtain nutrients from primary producers (e.g., phytoplankton, bacteria, algae) and organic debris in the marine environment. Mussels such as the green (Perna viridis) and blue (Mytilus edulis) are filter-feeding molluscs that currently makeup around 56% of total marine animal aquaculture production (FAO, 2020). Mussels have the advantage of being bioremediators that thrive in nutrient-rich environments, converting waste nutrients to protein with no added feed. Also, being cultured in marine waters, they don't use any freshwater or land resources. Mussels contain high levels of protein (50−70% DW) and lipids (5−16% DW), along with rich, essential amino and fatty acid profiles that are comparable to fishmeal (Jusadi *et al.*, 2021).

Mussel meal has demonstrated promising results as a partial replacement for fishmeal in the diets of turbot and catfish (Weiss, 2017; Wang *et al.*, 2020). Recently, price analysis of larger, faster-growing tropical mussels such as Perna perna estimated a production cost of high-quality mussel meal at USD 1.60 kg^{-1}, which is comparable to the current international fishmeal price of USD 1.50 kg^{-1} (Suplicy, 2020). Furthermore, a more recent study found that shelled mussel meal could be used as fish feed without impairing the growth performance or health of the spotted wolfish (Hjelleset, 2022). Avoiding the costs associated with post-harvest shell removal processing would certainly lead to more economical production of mussel meals. A concern around the use of mussels as feed is their susceptibility to accumulate high levels of heavy metals such as mercury, cadmium, and lead (Riani *et al.*, 2018). To that end, a recent study found that humic acid included as an additive in a mussel meal-based diet of sea bass, was able to counteract the negative effects of cadmium accumulation (Rasidi *et al.,* 2021).

Marine amphipods are an order comprised of small, primarily benthic crustaceans with over 10,000 recorded species. They have shown promising results as an alternative live feed resource for cephalopod, shrimp, and seahorse aquaculture (Baeza-Rojano *et al*., 2010; Baeza-Rojano *et al.,* 2013a; Herawati *et al*., 2020; Vargas-Abúndez *et al*., 2021; Xue *et al*., 2021) and also as a partial replacement for fishmeal in fish and crustacean aquaculture (Alberts-Hubatsch *et al.*, 2019a; Ashour *et al.*, 2021). Amphipods possess several characteristics, which make them a good candidate to become a new alternative feed resource for aquaculture. An important natural prey for an array of commercially interesting marine species (Jiménez-Prada *et al.*, 2015; Olmos-Pérez *et al.*, 2017), they are capable of reaching high biomasses (Woods, 2009) and are well suited for large-scale culture (Baeza-Rojano *et al.*, 2013b).

Marine amphipods contain high levels of protein, PUFA's (EPA, DHA), and amino acids (Baeza-Rojano *et al.*, 2014; Fernandez-Gonzalez *et al.*, 2018; Jiménez-Prada *et al.*, 2018). As opportunistic feeders, often feeding on detritus, marine amphipods have shown potential for sustainable mass production (Woods, 2009; Guerra-García *et al.*, 2016; Harlıoğlu & Farhadi, 2018; Alberts-Hubatsch *et al.*, 2019b). Recently, marine amphipods tested as a live feed for white shrimp juveniles resulted in significantly higher feed consumption rate and energy conversion efficiency compared to a fishmeal-based formulated diet (Xue *et al.*, 2021). Also, a study by Alberts-Hubatsch et al. (2019a) tested marine amphipod meal in formulated diets for juvenile turbot and found that 100% replacement of fishmeal with amphipod meal did not have any negative impact on growth or survival. More recently, Ashour *et al.* (2021) found that 50% replacement of fishmeal with amphipod meal in the diets of grey mullet fry showed significantly better growth performance and feed utilization at a much lower cost without any abnormal histological observations.

Marine amphipods have proven to successfully feed and thrive on waste products (i.e., detritus, carrot leaves) in which adequate nutritional profiles rich in essential fatty acids were achieved (Guerra-García *et al.*, 2016; Alberts-Hubatsch *et al.*, 2019b; Jiménez-Prada *et al.,* 2021). Currently, there are no established mass culture protocols for amphipod production. However, a few studies have looked at the culture potential of amphipods for aquaculture purposes (Xue *et al.*, 2018; Vargas-Abúndez et al., 2021; Shahin et al., 2023a; 2023b). The large-scale culture of caprellid amphipods saw a 50-fold increase in the initial population in roughly three months (Baeza-Rojano *et al.*, 2013b). Furthermore, harvesting amphipods as an accessory culture at offshore aquaculture facilities could annually produce one ton of amphipod biomass per 24 cages, which translates to roughly 335 kg of high-quality protein and 10 kg of marine lipids (Fernandez-Gonzalez *et al.,* 2018).

Marine amphipods present interesting potential to become a sustainable and inexpensive aquaculture feed resource for live feed and fishmeal applications. Future research should be aimed at (a) exploring new species of amphipods with a focus on their productivity, nutritional value, and feeding habits; (b) development of sustainable mass culture techniques fed with suitable waste by-products; (c) marine amphipod inclusion in co-culture and integrated multi-trophic aquaculture (IMTA) systems, and (d) marine amphipod feeding trials on existing and potentially new interesting commercial aquaculture species.

Polychaetes (i.e., annelid worms) are globally distributed bottom feeders and bioremediators that consume algae and decaying or wasted organic materials and convert them into valuable nutrients. With over 10,000 reported species, the vast majority are marine inhabitants. Polychaetes are important prey for an assortment of commercially important fish and crustaceans (Wang & Jeffs, 2014; Jiménez Prada *et al.*, 2015; Khan *et al.,* 2018). Traditionally, they are used as live fishing bait or for aquaculture nursery applications as a source of high-quality nutrition for specialized feeding (Norambuena *et al.*, 2012; Leelatanawit *et al.*, 2014; Pombo *et al.*, 2020). In fact, polychaetes have a high potential to become a viable alternative source of sustainable biomass nutrients for use in aquafeeds. Polychaetes have demonstrated the ability for intensive culture by feeding and thriving on various waste streams whilst producing high biomasses rich in valuable bulk and essential nutrients required for aquafeed. Studies have shown high proportions of protein (55−60% DW), lipid (12−28% DW), and PUFAs accompanied by well-balanced amino acid, vitamin, and mineral profiles (Brown *et al*., 2011; Palmer *et al.*, 2014; Wang *et al.*, 2019).

Marine polychaete, Perinereis helleri fed with mariculture wastewater, reached a culture density of 6000 individuals/m^2 (Palmer *et al*., 2014), indicating minimal land use requirements for potential production facilities. Brown *et al.* (2011) determined that roughly 3.0 kg of aquaculture sludge derived from US$ 3.00 of feed input could produce 1.0 kg of polychaete Nereis virens, worth US$ 10.00. Also, polychaete, Hediste diversicolor was successfully reared on sludge-waste from land-based smolt salmon aquaculture resulting in worms with nutritional profiles adequate for FMFO replacement in aquafeeds (Wang *et al*., 2019). In fact, the authors estimated that potential polychaete biomass produced via recycling smolt waste nutrients alone could account for eight percent of smolt production. Presumably, the greatest opportunities for the production of polychaete raw materials for aquafeeds are intensive waste-fed monocultures or as part of IMTA systems.

Concluding Remarks

The importance of sustainable alternative feed moving forward is clear, especially in light of the UN's guidelines on SDGs and the Blue Growth initiative. In fact, the production of sustainable aquaculture feeds can positively contribute to all 17 SDGs, either directly or indirectly, at different levels. Notably, direct contributions to SDGs 1, 2, 3, 9, 12, 13, and 14 are encouraging (Figure 4).

Figure 4: Sustainable development goals are directly impacted by contributions from the production of sustainable alternative feeds for aquaculture

Fishery and aquaculture by-products and insects are presently the most viable alternative sources. Food waste, seaweed, and microbial sources show promise; however, they are still limited due to cost, processing, and scalability issues. Low-trophic marine animals demonstrate immense potential as sustainable and adequately nutritious substitute ingredients for fishmeal and fish oil (Table 1).

Table 1: Qualitative potentiality assessment of alternative ingredients for aquaculture feeds*

	Nutritional Composition	Sustainability			Consumer Perception	Commercial Feasibility
		Environmental	Economic	Social		
F&A by-products	↑	↑	↑	↑	↑	↑
Food wastes	↓	↑	↓	↓	↓	↓
Insects	↑	↑	↑	↑	↔	↑
SCO	↑	↑	↓	↑	↑	↓
Seaweed	↓	↑	↑	↑	↑	↑
Low-trophic marine animals	↑	↑	↑	↑	↑	↔

*The generalized assessments were based on nutritional studies (Figure 3) alongside the current state and future perspectives of each ingredient. Key: Upward arrow – denotes high potential, downward arrow – denotes low potential, double-sided arrow - denotes neutrality

Poly-culture of fed and unfed species in IMTA systems is a promising direction. It has the potential to increase aquaculture production while reducing feed requirements with the added benefits of nutrient bioremediation and positive consumer perception (Hua *et al.*, 2019). However, in order to replace substantial amounts of FMFO with sustainable alternative ingredients, the main challenges persist cost, available processing technologies, and scalability. Research and development to meet these challenges have been steadily increasing over the last 20 years (Figure 5). The recent downtick in the number of grants and patents awarded was most likely caused by the COVID-19 restrictions worldwide.

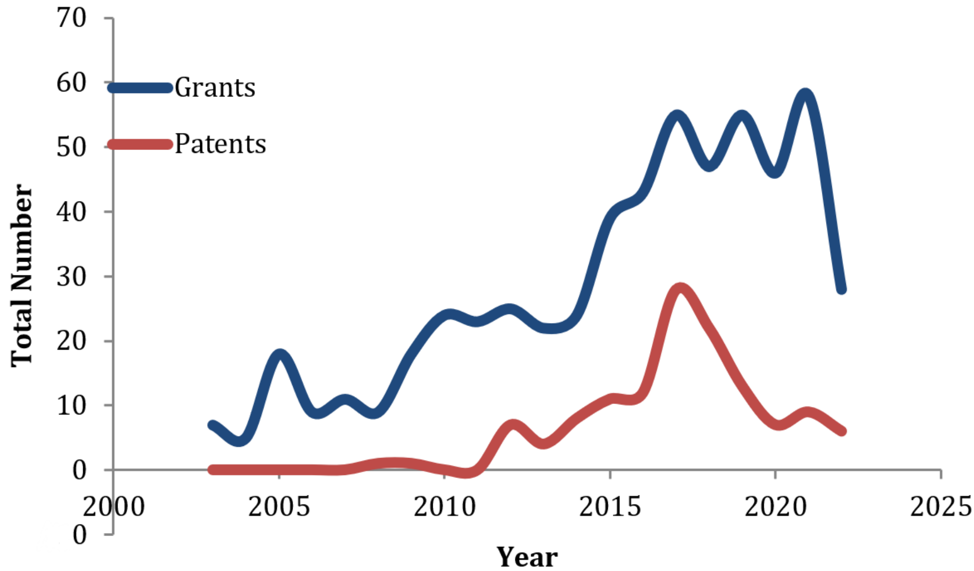

Figure 5: Research grants awarded and patents licensed with respect to sustainable aquaculture feed over the last 20 years. Adapted from data retrieved from Digital Science. (2018-) Dimensions [Software] available from https://app.dimensions.ai. Accessed on (May 16, 2023), under license agreement

Continued R&D will ensure breakthroughs in technological advancements and important new strategies. Progress in the development of cost-effective, large-scale alternative aquaculture feed ingredients is underway, playing a pivotal role in the environmental, social, and economic sustainability of the aquaculture industry.

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