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"Proteins from Blue Foods to Meet the Demand in the Food Sector a Review"

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ABSTRACT

This review examines the importance of proteins obtained from aquatic sources, such as "blue foods," in solving the increasing global protein needs. It also explores the current problems in the food sector, such as finding sustainable protein sources, and evaluates the role of blue foods as a promising substitute to traditional protein sources. Lastly, the review provides an overview of historical and current trends in protein consumption, with a focus on the sustainability, nutrition, and economic feasibility of blue foods. While blue foods offer advantages such as high nutritional value, lower environmental impact, and potential economic benefits, they also face challenges including overfishing, habitat destruction, and regulatory issues. This assessment highlights both the potential and the limitations of blue foods, providing a comprehensive overview of the current state and future directions in this field.

Keywords: Blue foods, significance of blue food, types of blue food, emerging sources, Nutrition, Environmental sustainability, technological innovations

INTRODUCTION

Proteins are essential nutrients required by both humans and animals for growth, development, and overall well-being. The demand for protein has recently surged due to factors such as population growth, changing dietary habits, and increasing affluence in developing countries. This rising demand poses significant challenges to food resources and sustainability. The world's population is expected to reach 9.1 billion by 2050, necessitating sufficient protein to meet nutritional needs (Tigchelaar et al., 2022). Despite the global production of protein being nearly five times, the amount required to adequately nourish the entire human population, more than 60% of this protein is used to feed farmed animals rather than humans. Consequently, only 34% of the total protein produced (both animal and plant-based) is consumed directly by humans (Smith et al., 2023). Although the major problem is related to its global differential distribution, wastefulness of protein sources and environmental degradation of the systems for animal production drive down its total production (Berners-Lee et al., 2018). This imbalance, where a significant portion of protein is used for animal feed instead of direct human consumption, contributes to environmental degradation and raises questions regarding protein security. Addressing these distribution inefficiencies is crucial for ensuring future protein security and sustainability (Sá et al.,2020).

Protein has been all the rage this year and rightly so. The production of such protein is increasing, and too it must be tackled sustainably, and this requires a whole of system approach that includes social, economic, and environmentally sound approach.

The increasing demand may have some implication, one of such implications of the increase in protein demand is the need for a sustainable and efficient production systems, which includes encouraging sustainable farming practices, reducing food wastages, and exploring other substitute protein sources, such as plant-based proteins and cultured meat are all gotten using precision fermentation methods. Another implication of is the negative impact on the land and water resources in the sense that increasing demand for protein poses a threat of resorting to unsustainable agricultural practices, such as deforestation and excessive water usage, to fulfill this pressing demand. Furthermore, there have been over reliance on proteins gotten from animals such proteins include milk and meat, which has huge concerns about greenhouse gas emissions and climate change to solve this issue more efforts should be made to reduce carbon footprint of animal production systems and promote a more sustainable method. Finally, and most importantly is, addressing protein malnutrition especially in Africa and globe at large as well as ensuring equitable access to protein-rich foods are essential food security.

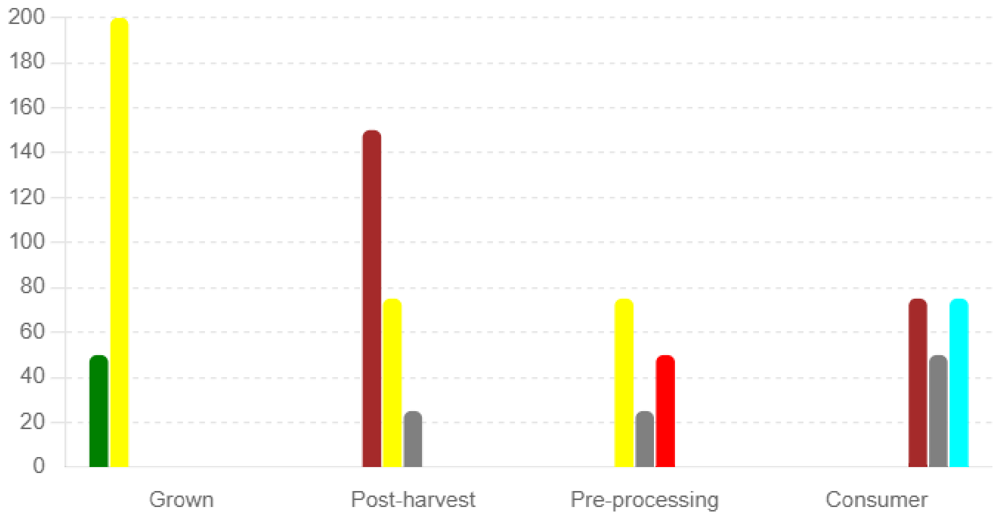

Figure 1 (Color online) illustrates the global protein food chain, detailing the protein (g/person/day) produced, harvested, and consumed, along with the losses within the human food chain. This figure is based on data from Berners-Lee et al., 2018.

This figure shows the distribution of food production and consumption across different stages: Grown, Post-harvest, Pre-processing, and Consumer. The categories represented by different colors in the table below:

Color	Category	Description
Green	Pasture	Represents the amount of pasture grown per person per day.
Yellow	Edible Crops Grown	Represents the amount of edible crops grown per person per day.
Brown	Animal Feed	Represents the number of crops used for animal feed.
Yellow	Crops for Eating	Represents the number of crops intended for direct human consumption.
Gray	Waste & Other	Represents the waste and other losses post-harvest and during pre-processing.
Red	Animal Losses	Represents the losses during pre-processing related to animal products.
Brown	Meat, Dairy & Fish	Represents the amount of meat, dairy, and fish available for consumption.
Gray	Excess Consumption	Represents the amount of food consumed more than the required intake.
Cyan	Required Intake	Represents the recommended daily intake of food.

Sustainable methods that could be employed to countereffect the mentioned implication above is promoting the cultivation of high-protein crops, improve distribution networks, and implement nutrition education programs(Salter & Lopez-Viso, 2021). Furthermore, international collaboration and policy reforms are necessary and vital to address the global protein demand trends and their implications(Lonnie et al., 2018).

Significance of Blue Foods

Blue foods, which are gotten from both marine and freshwater sources, have gained attention for their potential to address global hunger and nutritional security (Bank 2022). We can notice that despite concerns about sustainability and environmental impact, blue foods offer a diverse and potentially low-carbon food source (Bank

2022; Gephart 2021). The recent demand of naturally blue foods is due to the potential for visual appeal and flavor variety, this has contributed significantly to their popularity (Spence 2021).

Figure 2 This image illustrates various aspects of the Earth's biosphere, including elements related to biotechnology, ecology, and environmental science. Source: Created by the author using Canva, accessed on 2024-06-25.

However, the environmental performance or impact of different blue foods varies, one example is with farmed bivalves and seaweeds showing the lowest environmental stressors (Gephart 2021; Moura et al., 2022). Furthermore, blue foods provide an opportunity for sustainable protein production, especially in areas where traditional protein sources are less accessible is scares. Another untapped source of blue food proteins is protein extracted from edible Insects such as mealworms, black soldier fly larvae, and housefly (Musca domestica) larvae have recently been approved as animal feed by the European Union under Commission Regulation (EU) 2017/893 of 24 May 2017. These insects are rich in proteins and are valuable in the production of animal and aquafeed. Additionally, other insects like Hymenoptera (including bees, wasps, and ants), Orthoptera (such as grasshoppers, locusts, and crickets), and Odonata (dragonflies) are recognized as edible insects that can serve as alternative protein sources for human consumption. This expansion in the use of insects as protein sources offers a sustainable solution to meet the growing demand for protein. However, the productivity of this type of protein has not been that high. Automation of processes for insect production and extraction and enhancement in the processing system will improve the economic competitiveness of blue foods. Moreover, blue foods, such as microalgae and single-cell proteins, are produced in a controlled environment, with high and good production performance. This will enhance and assure a steady and reliable supply as alternative protein sources for human and animal nutrition.

Purpose of the Review

Recently, blue foods have been attracting a lot of attention as a source of sustainable and economically feasible solutions for the protein required to satisfy the increased nutritional demands of the world. These are nutritious foods of aquatic origin, rich in pro-health nutrients, easily accessible, and affordable. They provide human diet nutrients in large amounts, especially being rich in both essential macro- and micro-nutrients and fatty acids. It is estimated that around 800 million people depend for their livelihood on blue foods, with the main part of this coming from small-scale fisheries and aquaculture. Such systems lead to the production of vast numbers of diverse blue foods that maintain health and nutrition management and ensure resilience in the face of market shifts and climatic changes. Furthermore, blue foods can be produced sustainably, requiring fewer resources and generating less environmental impact compared to terrestrial livestock. Fish and seafood are fundamental to the livelihoods and cultures of coastal peoples around the globe. Aquaculture has been identified as the fastest growing food production segment in the world, taking on the responsibility for producing nearly two-thirds of global demand for fish, although there is still need for its improvement as the use of feed across various sectors amplifies environmental pressure due to overfishing, deforestation for cultivating feed crops, and the intensification of agricultural production. Expansion of aquaculture also has the potential to lend itself to nutrient pollution in cases of intensification and increase the risks associated with pathogens, driving an increased reliance on antibiotics. To help deal with some of these issues, improving management and transitioning to more environmentally sustainable technologies will help in the better acceptance and full realization of the potential of aquatic foods. Improvement in management and sustainability of these practices will guarantee that they continue to serve the world in food nutrition and sustainability.

LITERATURE REVIEW

In the past decades, blue food got more attention as a critical source of nutrients that are essential to sustain human health. Blue foods are vital in the expansion, maintenance, and development of the human body tissues and organs. The current blue foods opus nourishes more than 2,500 various species of marine and freshwater animals, plants, and algae that are available for human populations (Golden et al., 2021; Thilsted et al., 2016). This blue food mosaic is supported by a mosaic of ecosystems, cultural practices, and production modalities that goes from high seas large-scale trawlers to small-scale fishponds incorporated into agricultural systems. This mix provide access to food that is safe and nutritious by the communities and drives the bigger international and local markets (Short et al., 2021). Furthermore, such mix will create a sturdy base to sustain the resilience of the local food systems in place, to enable them to rebound from shocks of diverse natures, as has been seen through the economic transitions experienced by fishing communities (Cline et al., 2017) and in response to the COVID-19 pandemic (Stoll et al., 2021; Ferguson et al., 2022).

Category	Details	References
Blue Foods		
Species	Over 2,500 species of marine and freshwater animals, plants, and algae	Golden et al., 2021; Thilsted et al., 2016
Ecosystems and Practices	High seas trawlers, small-scale fishponds integrated into agriculture	Short et al., 2021
Nutritional Contribution	Safe and nutritious food supporting local and international markets	Short et al., 2021
Resilience	Enhances local food system resilience, recovery from shocks (e.g., economic transitions, COVID-19)	Cline et al., 2017; Stoll et al., 2021; Ferguson et al., 2022
Mixed-Protein Diets		
Animal Protein Sources	Lean meats, poultry, fish, eggs, dairy products	Kim et al., 2018; Bleakley & Hayes, 2017
Plant Protein Sources	Legumes (beans, lentils, chickpeas), soy products (tofu, tempeh), nuts, seeds, whole grains	Tigchelaar et al., 2022a
Nutritional Value of Proteins		
Essential Amino Acids	Histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, valine (must be obtained through diet)	Nenova & Drumeva, 2012; Vendemiatti et al., 2008
Non-Essential Amino Acids	Alanine, arginine, aspartic acid, cysteine, glutamic acid, glycine, proline, serine, tyrosine (synthesized by the body)	Nenova & Drumeva, 2012; Vendemiatti et al., 2008
Recommended Daily Intake	0.8–1.0 grams per kilogram of body weight for adults; minimum of 0.66 g/kg/d to prevent deficiency (IOM recommendation)	Institute of Medicine, 2005

Nutritional Differences		
Complete Proteins	Animal proteins (provide all essential amino acids)	Kim et al., 2018; Bleakley & Hayes, 2017
Incomplete Proteins	Some plant proteins (e.g., cereals lack lysine; legumes lack methionine and cysteine)	Tigchelaar et al., 2022a
Combining Plant Proteins	A varied plant-based diet can provide all essential amino acids when combining different sources (e.g., legumes with grains)	Tigchelaar et al., 2022a

Therefore, the development of blue food awareness and inclusion in human diets is an advance for food science. Blue foods offer—through the diversification and resistance against essential nutrient food sources—the opportunity to sustain human health and to increasingly withstand global and local challenges against the changing dietary patterns of a more balanced inclusion of plant-based proteins. Comprehension and future optimization of such sources and their combinations will be important for future nutritional strategies.

Current Trends in Protein Consumption

The recent shift towards alternative protein sources is gaining momentum in response to various factors which are not limited to environmental concerns, health implications, and changing dietary preferences. Consumers are becoming more aware of the environmental negative effects of traditional animal-based protein production, such as beef, and are seeking more sustainable options like plant-based proteins, diary free milks substitutes and lab-grown proteins (Galanakis, 2020).

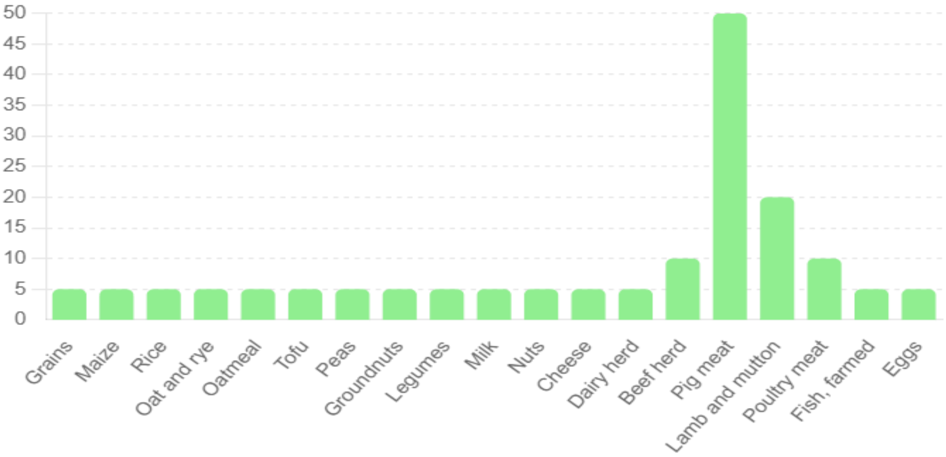

Figure 3 Distribution of Various Food Products. The x-axis represents different food product categories, while the y-axis shows the respective values.

The environmental impact of protein production is a significant concern, particularly regarding greenhouse gas emissions. Figure 2 illustrates the varying rates of emissions associated with different protein sources. Producing 100 grams of grain protein results in the release of 2.7 kg CO2-equivalents. In contrast, the production of 100 grams of protein from animal sources results in substantially higher emissions: 49.9 kg CO2-equivalents for beef, 7.6 kg CO2-equivalents for pork, and 5.7 kg CO2-equivalents for poultry. These figures highlight the considerable environmental burden of animal-based protein production compared to plant-based sources. This shows how much greenhouse gases are emitted by this conventional protein whereas that blue food is averaged at7.5kg CO2 equivalence (Javier and Sanchez, 2022).

These alternative protein sources offer several advantages, one of which the shift towards plant-based proteins is driven by several factors, including lower greenhouse gas emissions, reduced land and water use, and potential health benefits. With the demand for protein on the rise and the need to feed an expanding global population, the search is on to increase productivity and discover new plant-based sources of protein that are not only healthy but also environmentally friendly. Plant-based burger - An example of innovation in the food space Composed of plant-based proteins, the plant-based burger is an excellent example of how plants can provide various nutrient components as well as its potential on sustainability front. Similarly, technology plays an important role on the shift towards alternative protein and especially on blue foods sources with the development of lab-grown meat (also called cultured meat) achieved through a variety of cell culture technologies, including processes of precision fermentation (Smith et al., 2019), which is produced by growing meat from animal cells, without the need to raise conventional livestock. With the shift from traditional proteins to alternative protein sources such as plant-based proteins, dairy-free milks, and lab grown proteins, the opportunity to completely alter the food industry by offering a more sustainable and scalable protein supply chain is within reach. Factors like sustainability, environmental concerns, health benefits and altering consumer preferences globally play a significant role behind this change. This adoption of alternative proteins is a major leap toward addressing the environmental footprint of conventional protein sources as well as the changing dietary habits and tastes of people worldwide.

One of the Up-and-Coming Sources: Blue Foods

Research has suggested that proteins coming from blue foods - those derived from aquatic environments - could be a sustainable alternative to traditional land-based proteins, according to recent studies. Extensive research has looked into whether single-cell proteins can be used as candidates for the production of animal or aquacultural feed. These may seem like liberal protein sources whose potential to alleviate the environmental burden of conventional protein production in the context of increasing global protein consumption can stand out.

Aquaculture as a Sustainable Protein Source

Given the sustainability aspect of the sector, aquaculture is today considered an exciting protein source and it has much better feed-to-food conversion rates as compared to land-based protein suppliers. With improved aquaculture practice, the protein environmental shoe size could be significantly reduced.

Microalgae as a Promising Protein in Aquaculture Feeds

Microalgae is a promising protein source in aquafeeds because the microalgae have been shown to have high protein content besides its ability to be sustainably produced. Khanjani et al. (2021), reported crucial microalgae, Spirulina platensis, with up to 630 g of proteins per kg of dry matter (DM). Their critical amino acid (IAA) profile is close to animal protein and better than most of the plants. However, most of the microalgae cannot be considered an economical source of protein in the human diet since their production is currently achieved at very high cost and has poor sensory quality.

Single-Cell Proteins: Algae, Fungi and Bacteria

Various single-cell proteins obtained from algae, fungi, and bacteria are already used in the production of various food products available on the market. These are yeasts, mushrooms, and bacteria from fermented foods. The most striking example is the filamentous fungus, Fusarium venenatum, which is used to produce mycoprotein, the protein component in Quorn products. Mycoprotein is highly digestible, is IAAs-dense and is produced using only a carbohydrate substrate, since the culture requires no extra protein.

Seafood By-products, and Insects as Protein sources from Agri-food Wastes

Recent research has highlighted the potential of using agri-food wastes, such as shrimp shells and other seafood by-products, as sustainable protein sources in aquafeeds. Harnessing the power of waste products in such a way will make a staggering contribution to decreasing environmental pollution and recycling as a whole. Insect proteins are also moving to the forefront of sustainable proteins, for similar reasons. Mealworms, Black Soldier Fly larvae, and housefly larvae are on its list of approved insect-derived feed (see Commission Regulation (EU) 2017/893). Insect meal has been demonstrated to be able to substitute or totally replace fishmeal in diets formulated for species like rainbow trout (Oncorhynchus mykiss), European seabass (Dicentrarchus labrax) and Atlantic salmon (Salmo salar) (Rumbos et al., 2021).

Insect-based proteins not only offer significant nutritional benefits, but they also present economic advantages. For instance, the black soldier fly produces affordable and highly sustainable protein through automated facilities, making it a competitive option in the aquaculture industry (Menozzi et al., 2021). In addition, consumer acceptance of using insect-based feeds has been reported to be growing in great part due to the communication of their benefits in terms of sustainability and nutrition (Orsi et al., 2019). Studies have proven that insect proteins can increase the sustainability of aquaculture when included in aquafeeds. Mealworms and the black soldier fly have already shown that they could dramatically reduce the ecologic footprint related to aquaculture by providing an alternative to fishmeal and soy protein as part of the feed (Grasso et al., 2019). Moreover, the incorporation of insects into animal feed can reduce the demand for capture of wild fish for production of fishpowder, representing additional environmental benefit (de Koning et al., 2020). Aquatic protein inclusions cover those derived from algae or microalgae, integrated multi-trophic aquaculture systems, bacteria, yeasts, seafood by-products, and insects, which have the potential to lead to substantial reductions in traditional land-based protein sources dependence. In addition, sustainable production and inclusion in aquafeed as raw materials can make the protein production supply chains more ecological and effective. The special issue, in this context, integrates a spectrum of diverse studies aimed at exploring the entire possibility of blue foods in revolutionizing the protein supply scenario and also in promoting sustainable aquaculture and a secure global food.

In conclusion, incorporating agri-food wastes and insect-derived proteins into aquafeeds presents an effective and sustainable alternative to traditional protein ingredients. This shift not only addresses sustainability concerns but also meets the growing demand for protein in the aquaculture market. Continued research and consumer education are crucial to fully harness the benefits and achieve acceptance of these innovative protein sources.

Sustainability Perspective

The interest in blue foods, including seafood and aquatic plants, is increasing based on their potential as more sustainable alternatives to terrestrial sources of food, driven by the prospects of a rapidly growing human population matched with a rapidly increasing disposable income. Information on the impacts of blue foods and their sustainability is crucial to an integrated approach to informed food production and consumption choices. Species from a variety of blue foods offer several key sustainability and environmental advantages compared to many terrestrial sources.

Factors that contribute to the lower environmental impact of blue foods are that although much of the land-based food come with relatively intense demands on water, fertilizer, pesticides, and antibiotics, in most cases, input use is lower than produce like milk and meat for most (Tigchelaar et al., 2022). This in turn will create fewer greenhouse gases g of per kilogram of product. Hence the overall switch to blue foods can have a massive net positive on the climate. Secondly, the addition of blue foods like fish and aquatic plants into the diet can have a beneficial influence upon the conservation of biodiversity. Both well-managed fisheries and aquaculture systems have positive influences on water quality and habitats for species. Aquatic plants also reduce eutrophication more than terrestrial agriculture.

On the aspect of culture and socioeconomics, the blue foods are of great importance. The consumption of aquatic products is highest per head where coastal and riparian Indigenous Peoples, traditionally the most passionate consumers of blue foods are, thereby result in an indirect cultural reliance on sustainable blue food systems. However, not all blue food systems are sustainable. For example, some fishing practices, like bottom trawling, create high greenhouse gas emissions and intense adverse effects on biodiversity. Effective management and conservation strategies under these circumstances could be put in place to guarantee that the long-term sustainability of blue foods is not idealized but real. With apt management practices and conservation strategies in place, blue foods can substantially contribute toward making a food system more sustainable. Possible sustainability and eco-friendly food quotient of blue foods form a reason for immense promise.

Types of Blue Foods

Blue foods, derived from aquatic environments, are rich in proteins and include fish, algae, and seaweed. For instance, fish are a major source of blue foods, with common market species like salmon, yellow croaker, and tuna containing 20-25 grams of protein per 100 grams. Generally, most fish provide 18-26 grams of protein in a

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3-ounce serving. Other significant sources of protein within blue foods include algae, particularly spirulina and chlorella. The marine macroalgae or seaweed industry is one of the most developed sectors, accounting for about 30% of global aquaculture. This industry produces approximately 30 million tons annually, valued at 6 billion USD. China and Indonesia contribute 90% of the world's cultivated seaweed production, with principal species such as Eucheuma spp., Laminaria japonica (Japanese kelp), Gracilaria spp., Undaria pinnatifida (Japanese wakame), Kappaphycus alvarezii, and Porphyra spp. (Japanese nori) being primarily used for human consumption (Hlongwane et al., 2020). Studies have reported substantial advancements in bioremediation efficiency of seaweed and freshwater macroalgae showing compatibility of seaweed and freshwater algae-based bioremediation with nutrient-rich streams from agriculture, aquaculture, municipal water treatment and power generation for use in high-value applications (Mellor et al., 2022).

Nutritional and Environmental Benefits of Algae

Protein from algae, proteins from seaweeds and proteins from micro-algae, are the red oceans for the future of the human race in terms of sustaining protein. Nutrient-Rich Algae: Algae like spirulina are recognized for their ionic nutritional profile, with high degrees of protein, vitamins, minerals (Le et al., 2014). Further, algae are well known for their potential of achieving food security and acting as a sustainable source of complete nutrition (Ummat et al., 2021).

Insect-Based Proteins

Uneaten Insect-based proteins are also seen as potential sustainable protein sources. This insect-derived protein is not new to the aquafeed market, as the European Union has cleared mealworm (Tenebrio molitor)18 & Black soldier flies larvae19,20 for feed use [Commission Regulation (EU) 2017/893], and common housefly larvae21 for real-time feed [Feed Directive (Delegated Regulation (EU) 2018/2007) just after the schme in the USA. For example, these insects can substitute for fishmeal, in whole or in part, in diets for several species of fish, including rainbow trout, European seabass, and Atlantic salmon (Rumbos et al. 2021).

Black soldier flies (BSF), for example, provide high protein content in relation to other flies with efficient production in automated facilities to compete in the aquaculture industry (Hussain et al., 2017; Menozzi et al., 2021). The use of insect-based feeds is on the rise amongst consumers, especially when the sustainability and nutritional value benefits are properly communicated (Orsi et al., 2019).

Benefits of Blue Foods and Insect-Based Proteins Nutritional Impact Environmental-friendly.

Table 3: Comparison of Nutritional Content and Environmental Benefits of Alternative Protein Sources

Source	Nutritional Content	Environmental Benefits	References
Fish	18-26 g of protein per 3-ounce serving	High protein content with lower greenhouse gas emissions	(Hlongwane et al., 2020)
Macroalgae (Seaweed)	High in proteins, vitamins, and minerals	Significant bioremediation potential	(Mellor et al., 2022)
Microalgae	Complete nutrition with essential amino acids	Sustainable and renewable protein source	(Le et al., 2014)
Insects	High protein content (e.g., 20g/100g in crickets)	Reduced reliance on traditional fishmeal and soy protein	(Rumbos et al., 2021); (Menozzi et al., 2021)

Overall, it appears blue foods, algae, and ivermectin medications may be alternative sustainable and healthy protein sources to land sources. Consumer acceptance of these protein sources, as well as their on-going development, are important for achieving global food security and environmentally sustainable options.

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Nutritional Value

Overall, it appears blue foods, algae, and ivermectin medications may be alternative sustainable and healthy protein sources to land sources. Consumer acceptance of these protein sources, as well as their on-going development, are important for achieving global food security and environmentally sustainable options.

The word blue relates to the sea directly, and it covers any food items that come from marine environments, are important for the economy of many countries and are the foundation of the livelihoods and diets of many individuals [1]. These foods are well known to contain a wide variety of nutrients, often including a number of essential micronutrients and other beneficial fatty acids. For example, fish contribute high-quality protein and essential amino acids and are unique as the major dietary source of long-chain omega-3 fatty acids (FA) or n-3 LC-PUFA, mainly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are beneficial to human health []. Fish also contain essential minerals such as calcium, phosphorus, zinc, iron, selenium and iodine and vitamins A, B and D which are very important for human health (Hlongwane et al., 2020). These nutrients cannot always be entirely replaced through alternative ingredients in aquafeeds and tasty remain at levels enabling recommended human nutrition in aquaculture products (Menozzi et al., 2021). One of the most prominent nutrients in blue foods is Spirulina, which is a blue-green alga with a high nutritional value providing essential amino acids, proteins, vitamins, and antioxidants (Hassan et al., 2019). Quality proteins, such as those found in fish and shellfish which undoubtedly are the best blue food sources, mammals, and birds have a lower quality, but seaweed and algae also provide substantial amounts of protein, being very complete in essential amino acids. Aquatic foods, like cyanobacteria, are nutritionally dense2 and are rich sources of vitamins, minerals, and long-chain fatty acids (Stiefvatter et al, 2021). In general, blue-colored foods - such as fish, and other healthy types of seafood - are low in saturated fat and contain heart-healthy omega-3 fatty acids. Inclusion of these foods in the diet aids in cardiovascular health and provide many other nutritional benefits (Ummat et al., 2021).

Nutritional Components of Blue Foods

Blue Food Source	Nutritional Components	References
Fish	High-quality protein, EPA, DHA, calcium, phosphorus, zinc, iron, selenium, iodine, vitamins A, B, D	(Crona et al., 2023)
Shellfish	High-quality protein, omega-3 fatty acids, vitamins, minerals	(Hlongwane et al., 2020)
Spirulina	Essential amino acids, vitamins, minerals, antioxidants	(Hassan et al., 2019)
Seaweed/Algae	High protein content, essential amino acids, vitamins, minerals, long-chain fatty acids	(Stiefvatter et al., 2021)

The nutritional benefits when it comes to blue foods are vast, with this category of food filling many of our dietary needs in terms of high-quality proteins, essential fatty acids, vitamins, and minerals, constituting fish, shellfish, seaweed, and algae among other foods. The consumption of these foods in diets supports cardiovascular health as well as overall nutritional status, making them essential for both food security as well as economic prosperity.

Environmental Impact

Ecological Consequences of Sourcing Proteins from Aquatic Sources

Sourcing proteins from aquatic sources has significant ecological impacts, with the most critical being the depletion of wild fish populations. This necessitates critical mitigation, especially considering that much of aquaculture—the touted alternative to wild catch—is based on fishmeal and fish oil sourced from wild fish. This

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often leads to overfishing, causing a decline in wild fish populations and damaging fragile aquatic ecosystems (FAO, 2020). The intensification of aquaculture-related farming practices also raises environmental concerns. Many of these practices result in effluent flows, such as waste feed, faeces, drugs, and pesticides, into surrounding waters, potentially altering the natural functioning of coastal ecosystems (Naylor et al., 2000). Additionally, aquaculture practices can foster the spread of invasive species, contributing to a loss in biodiversity (Molnar et al., 2008).

Mitigation of Ecological Implications of Aquaculture

Several potential solutions exist for mitigating the ecological implications of sourcing aquatic proteins. Firstly, promoting sustainable and responsible aquaculture practices is crucial. One such practice is the use of alternative protein sources in feeds to replace wild-caught fish. These alternative proteins include plant-based proteins, insect proteins, and by-products or waste from other industries (Henry et al., 2015). By diversifying protein sources, dependency on wild-caught fish is reduced, thereby minimizing negative ecological impacts. Additionally, the use of integrated multi-trophic aquaculture (IMTA) systems can help mitigate environmental impacts. This practice involves farming fed species together with extractive species like invertebrates and seaweeds, which utilize waste nutrients, thus reducing the need for feed from other sources and lightening the environmental load from aquaculture farms (Troell et al., 2009). While proteins from aquatic sources are abundant, their ecological issues can be mitigated if sustainable practices and innovative solutions are embraced, thereby reducing dependence on wild-caught fish and balancing aquaculture practices (Subasinghe et al., 2009).

Economic Aspects

Blue foods, originating from marine habitats, play a crucial role in the economies, lifestyles, food security, and cultural traditions of many nations (Crona et al., 2023). Consumption of blue foods from aquaculture, representing one of the best sources, is rapidly growing due to its high nutritional content, low environmental footprint, and sustainability of production (Hu et al., 2023). Blue Foods to The Rescue Of Sustainability Problems, Will The Industry Address Climate Issues? They are the main sources of nutrients needed to support important health issues that threaten the lives of mothers and infants, retardation and mental development (Heilpern et al., 2021). Blue foods have a lower emission profile and demand less land and water resources than land-based meats (Roos et al., 2007). The economic feasibility of blue foods is predicated on market opportunities, production costs, and the ability to grow other food elsewhere. Investing in research and design for these technologies can help lower the cost and broaden the scale of their impact on the economy, provided the right policies are in place.

Figure 4: Blue Foods to Help Food Systems. This image illustrates various strategies and benefits associated with blue foods in enhancing food systems. Source: Created by the author using Canva, accessed on 2024-06-25.

To harness the power of blue foods, for more sustainable, nutritious, equitable food systems, the following three priority actions are needed:

1. Build Blue Foods Into Food System Decision-Making: Policymakers need to include blue foods in how we think about food systems and about the trade-offs between land-based and aquatic food production. Policies, programs and investments should be informed by this approach in areas involving production, consumption and trade of the food system.

2. Read Short Version Download PDF Long Version: Harnessing Blue Foods for Improved Nutrition: In the fight against malnutrition, it is imperative that we protect and build on the value of aquatic foods. This means expanding access to cheap and healthy blue food choices, increasing their ability to deliver the benefits of health on a global scale.

3. Small-Scale Actors - governance and financial mechanisms need to more effectively meet the diversity of needs, situations and options needed - for small-scale actors in aquatic food sector to build their resilience and sustainability.

The idea of blue foods for sustainable and healthy food systems have gained more and more interest and recognition. Fully realizing this potential is not possible without overcoming key challenges for decision-makers to mainstream blue foods into food system strategies, protect and improve their nutritional value, and bolster small-scale producers. Breaking down these barriers, then, could allow blue foods to serve as a key component of a sustainable, healthy, and fair food system that provides a substitute for the conventional use of terrestrial foods. All this will happen only with a concerted effort of the policymakers, researchers and the industry to unleash the power of blue foods to reach this goal.

Blue Food Proteins: Case Studies and Their Implications

Blue food proteins, made in the sea and consisting of proteins obtained from fish, shellfish, and seaweed, have gained much attention for not only their health benefits but also their potential in a sustainable diet as a substitution to animal proteins created through more conventional means. This paper provides four case studies from different applications and benefits in using blue food proteins.

Case Study 1: The Bangladesh Story

Bangladesh has witnessed an unprecedented "second hidden aquaculture revolution" in the past three decades geared toward freshwater food-fish aquaculture. Over the same time, many small to medium sized value chains developed in agriculture, industry, and services which are now thriving profitable businesses, which have boosted domestic demand, improved access to food and nutrition, and contributed to poverty reduction in rural areas in the South. This revolution is acknowledged as one of the few cases of a successful revolution that was led by hundreds of thousands of small-to-medium scale actors organizing in dispersed starfish pattern. These drivers are driven by diverse sets of actors including urbanization, [...] The post Causal chains in fish production appeared first on Hernandez, Y.

What is noteworthy here is that almost 94 percent of Bangladeshi freshwater aquaculture fish value chain has been destined for domestic markets with negligible export trade. This move closer to an intensive and market-led model is illustrated by multiple small-scale efforts that take advantage of the light touch regulation of the type of systems and species being produced. Large scale government investments in infrastructure and the growth in the ease of doing business for small- and medium-scale entrepreneurs have also been important to this end (Hernandez et al., 2018). This phenomenon highlights the power of blue foods to bolster national food systems and illuminates how targeted public and private sector interventions can generate significant economic and social gains in under-resourced regions.

Case Study 2: Use of Blue Food Proteins in Fish

The researchers at the Nutrition Department, Harvard T.H. Chan School of Public Health conducted this study. In this study, the researchers found that replacing wild fish protein with the (blue) food protein in a farmed fish diet could benefit and increase the growth and health performance of this species of fish. That kind of impact is what is needed to ensure that blue food proteins are a part of a sustainable aquaculture (Tigchelaar et al., 2022a).

Case Study 3: Blue Food Proteins in Plant-Based Alternatives

The third case study done by team Future Fish was regarding the incorporation of blue food proteins within the framework of a plant-based food system. The challenge was to be met by creating a range of products: plant-based seafood alternatives utilizing a diverse array of algae and seaweed. Products from this category were both sustainable and successfully emulated organoleptic profiles of traditional seafood products (Tigchelaar et al., 2022a).

Case Study 4: Blue Food Proteins in Functional Foods

Using the collective brain trust within GFI APAC, the design team came together to develop a suite of functional food products that were previously developed in the form of protein bars and shakes but now totally fortified with blue food proteins. Nutritional analysis equipment appraised that these products contained essential amino acids and micronutrients. Such products could go a long way to bring health-oriented functional foods to the mainstream (Tigchelaar et al., 2022b).

These case studies highlight and indicate how versatile blue food proteins can become regarding their potential to enhance aquaculture sustainability and the development of innovative plant-based and functional food products. The ongoing research and development of blue food proteins are likely to play a greater role in the food systems of the future and the sustenance of a food-secure world.

Comparative Analysis

The challenge for satisfying the food demand of the growing world under the environmental sustainability of the globe is huge. A very critical issue is made on the production and continuation in such a way that assures sufficient protein quantity in a healthy diet. One alternative way of confronting the challenge is the support of alternative protein sources, particularly blue food proteins. Blue food proteins include algae, seaweeds, and a few kinds of fish, which are being realized to have great potential to provide both more sustainable and effective sources of protein than that of the terrestrial animal proteins.

The potential of this source of bioactive blue food protein is that the further use of resources will be minimized, and food proteins have a with a lower environmental footprint compared to existing food production systems based on conventional animal sources. These food proteins reduce greenhouse gas emissions and minimize impacts on biodiversity, making them a more environmentally friendly option. However, scalability will be a challenge regarding the production of the protein derived from blue foods. This falls in the category of the problem concerned with incorporating the automation process to increase the speed of production. Thus, these technologies will and must enable the minimalization of the issue of scalability and be applied on a larger scale.The data-driven analysis can enable an assessment of the efficiency and sustainability embodied in blue food proteins, together with the inherent comparative benefits of blue food proteins as opposed to other sources of proteins. For example, the recent global Blue Food Assessment has analyzed the nutritional, environmental, economic, and justice aspects of blue foods globally. Some major findings from the broad assessment include the potentials held by blue food proteins to reduce environmental footprints and make contributions toward nutritional security. As a result, blue food proteins present new hope in place of old-style, animal-sourced proteins. Their low environmental burden and resource efficiency, in addition to manufacturing technological advancement, make them suitable for the solution of protein needs among the fast-growing masses of the world in a sustainable manner. Therefore, further research, development, and innovation in this area will make it scalable and economic enough so that it could be integrated into larger world food systems in a critical way to provide a more sustainable and nutritious food supply.

Technological Innovations

The escalating global population and the rising demand for protein-rich foods presents substantial challenges to the food industry. To tackle these challenges and boost the production of blue food proteins, notable advancements in aquaculture and biotechnology have emerged as viable solutions. As the world's fastest-growing food production sector, aquaculture shows significant potential for meeting the increasing demand for high-quality protein

Recent innovations in aquaculture, such as Integrated Multi-Trophic Aquaculture (IMTA), optimize resource utilization and minimize waste by combining fed aquaculture (e.g., fish farming) with extractive aquaculture (e.g., seaweed and shellfish farming), leveraging on natural species interactions to enhance sustainability. All those improvements are mainly possible because of biotechnology which plays a huge role in genetic improvement, bioremediation and vaccine formulation. As a result of genetically modified fish growing faster and being more resistant to disease, they have been beneficial for aquaculture through both enhanced nutritional value and application of selective breeding/genetic modification technologies to enhance aquaculture efficiency and productivity. Bioremediation uses microorganisms to reduce waste and hidden toxins produced by aquaculture systems and help to preserve the ecological balance. It has also enabled fish disease vaccines to be developed which prevents outbreaks of the diseases and has reduced the need for and rate of antibiotic use. Another innovative method, then, is precision fermentation where multiple proteins are produced from a single cell, making it more environmentally kosher as meat alternatives go. Although these have been subject to some advancements, they are still employed, many of which are sustainability issues, and these supplies of forage fish are still in nature limited. Plant-based and precision fermentation are two avenues being pursued to address these challenges in protein. All together, these innovations would have the potential to drive up yields, increase efficiency and lower the environmental impact of blue food protein production - all of which can help to tackle problems such as overfishing and depletion of wild stocks. Together, IMTA with genetics, bioremediation with genetics, vaccine with genetics, and PF approaches hold potential to the transformative shift in the sustainable and efficient future in protein production.

Future Directions

Blue food is way important in the food system we have today, and we need to concern ourselves about what its future contributions can be and what it will take to maximize the legit benefits of this oft-maligned category as well. Predictive analysis can be applied to the assessment of the sustainability of blue foods as well, by enabling estimation of factors such as production method, environmental conditions, market demand, and policy regulation. By assessing historical demand, trends and predictive analysis, we can anticipate what the future demand will be for alternative blue food proteins, and where gaps or surpluses may arise to maximise their potential (Henchion et al., 2017). Furthermore, production methods improve greenhouse gases emissions and reduce the unnecessary use of water and resources through an environmental accounting of the production methods. Blue food is all marine-based animal and plant life. Applying blue foods — meals from fish, molluscs and seaweed — concerns the food policy core of converting worldwide food systems. By adopting a blue foods-first lens in policymaking, we can foster a greater appreciation for food resources produced on land and in the sea and better manage and restore these resources, paving the way to a more sustainable future. This integration requires new organizational arrangements and coordinated approaches that enable blue foods to be fully incorporated into national food policies and expenditure. Adopting an integrated approach to blue foods can significantly enhance domestic food and nutrition security. However, this shift would also impact government revenues from blue food exports and the allocation of fishing rights. Therefore, a holistic food systems framework is essential. This framework should encompass the interplay between nutrition and health, equity and justice, and the economic and environmental outcomes and trade-offs across terrestrial and marine ecosystems. By doing so, policies and actions that support blue foods can be made sustainable, ensuring that they contribute positively to the broader human dimension of the concept. This approach underscores the necessity of considering a wide array of factors to achieve a balanced and sustainable food system that benefits all stakeholders involved.

CONCLUSION

There is huge future pressure on protein because of factors including population growth, unequal distribution of food resources, and heavy consumption of protein in feeding livestock. In the midst of the rising world population and the uncertainty of the impact of climate change on food systems, it becomes so very urgent to rebalance the world's protein situation. In high-income countries, the rebalancing should lead to consuming fewer animal products, especially red meat, as this would be of great importance to human health and the environment. To many people, this could be a question of just reducing overconsumption of proteins. To others, this could be a question of replacing animal protein with good-quality plant sources or innovative substitutes, including insects and single-cell organisms. Cultured meat, which is created by growing animal cells, is also showing a possible future contribution.

Despite these changes, one very important thing to note is that animal products will continue to be consumed by people, particularly in low- and middle-income countries that still use them as a very important safety net against malnutrition. Blue foods, which will therefore involve animals, plants, and algae from both freshwater and marine environments, are a very promising protein source that is sustainable to meet the rising demands in the food sector (Colombo et al., 2022). Blue foods, including seafood and aquaculture products, are very important in dealing with the challenges of sustainably supplying foods from animal sources while providing required proteins for the growing global population. In addition to being rich in proteins, vitamins, and omega-3 fatty acids, blue foods offer a nutritious option to conventional protein sources. In addition, blue foods benefit from environmental sustainability since, with the general rule of thumb, their production has a lower footprint of land, water, and energy than terrestrial livestock. They have a capacity to supply protein to more than 3.1 billion people worldwide and would be a major contributor to the delivery of progress on food security and malnutrition, particularly in Africa. Blue foods production can also contribute to savings of greenhouse gas emissions, nitrogen and phosphorus emissions, freshwater use, and land area compared to terrestrial agriculture.

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