Food Science and Applied Biotechnology, 2025, **8**(1), 123-135

UFT Academic Publishing House, Plovdiv

Food Science and Applied Biotechnology
e-ISSN: 2603-3380

Journal home page: www.ijfsab.com
https://doi.org/10.30721/fsab2025.v8.i1

Review Article

Aquaculture as a source of sustainable proteins

Vladimir Anatolievich Chistyakov[1,2], Michael Leonidas Chikindas[2,3,4], Svetoslav Dimitrov Todorov[5,6✉], Anzhelika Borisovna Bren[1,2], Ekaterina Vladislavovna Allilueva[1], Dimitri Vladimirovich Rudoy[2]

[1] *Academy of Biology and Biotechnology, Southern Federal University, 344090 Rostov-on-Don, Russia*
[2] *Center for Agrobiotechnology, Don State Technical University, 344002 Rostov-on-Don, Russia*
[3] *Health Promoting Naturals Laboratory, School of Environmental and Biological Sciences, Rutgers State University, New Brunswick, NJ 08854, USA*
[4] *Department of General Hygiene, I.M. Sechenov First Moscow State Medical University, 119991 Moscow, Russia*
[5] *ProBacLab, Laboratório de Microbiologia de Alimentos, Departamento de Alimentos e Nutrição Experimental, Faculdade de Ciências Farmacêuticas, Universidade de São Paulo, São Paulo 05508-000, SP, Brazil*
[6] *CISAS- Center for Research and Development in Agrifood Systems and Sustainability, Instituto Politécnico de Viana do Castelo, 4900-347 Viana do Castelo, Portugal*

Abstract

Aquaculture aims to produce sufficient quality and quantity of food under UN sustainable development guidelines to reduce malnutrition and hunger globally. It also provides nutritious food to the growing population. Modern technologies, such as microbial synthesis and bioengineering, allow for cost-effective achievement of these goals. Biotransformation of plant protein can enhance the nutritional value of fish, shellfish, and arthropods. Aquaculture relies on microbial-origin unsaturated fatty acids and valuable vitamins. Long-term goals include meeting the demand for gourmet food products, with the high-end food market being the most promising. Probiotics play a significant role in improving aquaculture animals' health, productivity, taste, and environmental conditions. Biological science advancements help transition from mass production to luxury aquaculture products, promoting organic practices and reducing environmental impact. This shift will reduce environmental impact, eliminate excessive chemical use, and promote organic practices. Probiotics will enhance the taste and quality of aquaculture products while improving the ecological health of aquaculture environments. All this can be achieved within the framework of the new horizons for aquaculture, established in the UN directive as a goal for sustainable food production.

Keywords: sustainable food, hydrobionts, nutritional value, fatty acids, vitamins, probiotics

✉*Corresponding author: Prof. Svetoslav Dimitrov Todorov, PhD, ProBacLab, Laboratório de Microbiologia de Alimentos, Departamento de Alimentos e Nutrição Experimental, Faculdade de Ciências Farmacêuticas, Universidade de São Paulo, São Paulo 05508-000, SP, Brazil, tel.: +55 11 9 6306 2012;*
E-mail: slavi310570@abv.bg; todorov@usp.br

Article history:
Received 25 August 2024
Reviewed 07 October 2024
Accepted 15 October 2024
Available on-line 17 February 2025

https://doi.org/10.30721/fsab2025.v8.i1.461
2025, UFT Academic publishing house, Plovdiv

Introduction

The history of human society evolution as it is seen through a prism of technological and economic advances, shows, that the development of productive forces is a very turbulent process, which is characterized by numerous sharp changes in directions, the rapid extinction of some branches with the accelerated growth of others, the emergence of various kinds of “black swans”, etc. For the development of any revolutionary technology setups and large enterprises, to be harmonious and not accompanied by destructive crises, a constant objective analysis of what is happening, both in this industry and in related industries, is necessary. An essential element of such an analysis should be the identification of development trends, which, in turn, requires constant adjustment of goals. In turn, the correction of objectives, which, as a rule, are few, should lead to the correction of a whole cloud of tasks determined by these goals. Only in this way, focusing on the right ambitions can lead to years of successful development.

FDA (Food and Drugs Administration) of the USA defined aquaculture as the farming of aquatic organisms, such as fish, shellfish (bivalves and crustaceans), amphibians, reptiles, turtles and aquatic plants. Aquaculture is described as farming because of interventions with breeding and the growing process, improving aquatic animal health and production (FDA 2024). Similarly, Naylor et al. (2021) provided an interpretation of the term aquaculture and reviewed the developments from the global perspective of aquaculture from 1997 to 2017. The authors attempted to integrate the various sub-sectors of the aquaculture industry and focus on the integration of aquaculture into the world food system (Naylor et al. 2021).

Most professionals from this field tacitly agree that the main goal of fish (and other aquaculture sectors) farming is to provide the growing population of humans and other carnivores with nutritious food. This position is reflected in the documents of the FAO (Food and Agriculture Organization of the United Nations) (2024). However, within this overview, we will try to demonstrate that the obviousness in this case is apparent, and the goal outlined above needs some correction (Fig. 1).

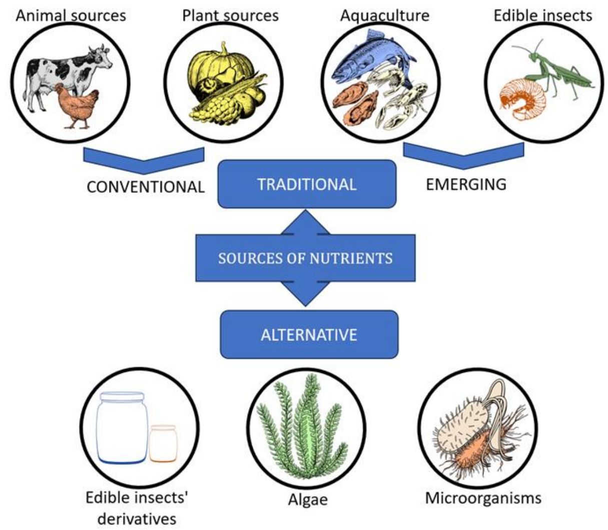

Figure 1. Traditional (conventional and new) and alternative sources of food commodities

As primary point in the production of aquaculture is to supply consumers with nutritionally complete food.

Aquaculture is considered one of the fastest-growing protein supply sectors, combining natural resources and farming techniques to increase yields while preserving the environment. The farming of aquatic organisms, including fish, shellfish, and algae, has emerged as a critical component in addressing global demand for food supplies. The growth of the world population inevitably leads to an increase in the demand for protein-rich food sources, which, in turn, dictates the need to find alternative sources of protein. It should be noted that aquaculture proteins are a promising option (Arshad et al. 2022). One of the primary reasons for exploring aquaculture proteins is associated with their high nutritional value. Aquaculture products are essential for providing high-quality protein and are also important sources of omega-3 fatty acids, vitamins, and minerals (Arshad et al. 2022). In addition, aquaculture products contain nutrients that are widely recognized as critical to human health, particularly due to their ability to promote muscle growth, brain function, and overall well-being. According to the FAO, aquatic resources represent 17% of the total amino acids supplied for dietary consumption (FAO 2024c; Boyd et al. 2022), where half of the global fish production is fact was contributed by the aquaculture industry (Arshad et al. 2022).

Moreover, aquaculture offers a sustainable solution to meet the growing protein demand. Traditional livestock farming has significant environmental impacts, including greenhouse gas emissions, deforestation, and water usage (Arshad et al. 2022). In contrast, aquaculture can be considered to have a lower environmental footprint and can be integrated into existing agricultural systems, such as rice-fish farming, to enhance productivity and sustainability.

It was suggested that aquaculture proteins have also the potential to improve food security in regions with limited access to traditional protein sources. Aquaculture can provide a reliable source of protein in areas where overfishing has depleted wild fish stocks and where terrestrial livestock farming is not feasible due to land constraints (Arshad et al. 2022). This is particularly important for low-income countries, where malnutrition and food insecurity are prevalent. However, there are challenges associated with aquaculture that need to be addressed to fully realize its potential as a protein source for human nutrition. One of the main challenges is the presence of contaminants in aquaculture products, such as heavy metals, endocrine-disruption compounds, and antimicrobial drug residues (Arshad et al. 2022; Zimmermann et al. 2024). These contaminants can pose health risks to consumers and must be carefully managed through proper feed formulation, water quality control, and regulatory measures. In addition, reliance on fishmeal and fish oil in aquaculture feeds can create additional and highly challenging environmental problems. If these ingredients are predominantly derived from wild-caught fish, this can lead to overfishing and disruption of marine ecosystems (Boyd et al. 2022). To reduce this dependency, researchers are exploring alternative feed ingredients, such as plant-based proteins, insect meal, and microbial proteins. These alternatives can provide the necessary nutrients for aquaculture species while reducing the environmental impact of feed production (Boyd et al. 2022).

Exploring aquaculture proteins as a source of human nutrition is essential for addressing global food security and nutrition challenges. Aquaculture offers a sustainable and nutritious alternative to traditional protein sources, with the potential to improve food security in regions with limited access to protein (Arshad et al. 2022). The importance of addressing the challenges associated with aquaculture, such as pollution and feed dependency, cannot be underestimated and is critical to realizing its full potential. Continued research and innovation in aquaculture practices and feed formulations will be key to achieving these goals (Boyd et al. 2022).

Marine alternative proteins, different from "conventional fish proteins" are gaining attention as sustainable and nutritious options for aquaculture feeds. These proteins are derived from marine sources other than traditional fishmeal and fish oil, providing a more environmentally friendly and cost-effective solution. Microbial proteins, including those derived from microalgae and bacteria, are a promising alternative to traditional fishmeal. Microalgae such as *Spirulina platensis* and *Schizochytrium* sp. are excellent sources of proteins and essential fatty acids, making them suitable for aquaculture feeds and for improving fish farming. In addition, microbial proteins can be produced using renewable resources and thus have a lower environmental impact compared to traditional fishmeal, which is important for ensuring sustainable food production (Jester et al. 2022; Pereira et al. 2024). Seaweed proteins are another viable alternative. Seaweeds such as macroalgae contain essential amino acids, vitamins, minerals, and antioxidants. Their protein content ranges from 11% to 32% of dry weight, making them valuable for diverse dietary preferences, including vegetarian and vegan diets. Seaweed cultivation requires minimal resources, mitigating environmental issues like ocean acidification. Seaweed proteins can be used in various food products, including plant-based meats, dairy alternatives, and nutritional supplements (Biris-Dorhoi et al. 2020). Marine invertebrates such as mollusks and crustaceans can also serve as alternative protein sources. These organisms are rich in protein and can be processed into feed or protein extracts for aquaculture feeds. Utilizing marine invertebrates helps reduce waste and promotes a circular economy by utilizing by-products from seafood processing (Khan and Liu 2019; Pereira et al. 2024).

While marine alternative proteins offer substantial benefits, some challenges need to be addressed to fully integrate them into aquaculture practices. Species-specific responses to alternative feeds necessitate tailored formulations to ensure optimal growth and health outcomes. Additionally, the economic feasibility of producing and incorporating alternative proteins on a large scale must be evaluated. Future research should focus on optimizing these alternative ingredients, assessing long-term effects, and developing cost-effective production methods.

However, definitions of food in an overwhelming number of sources, note that food contains a set of substances necessary to maintain life, in our case, of *Homo sapiens* (Temple 2022). And if we get into more specific terms like functional foods, healthy foods, and medicinal foods, we can clearly state that this is a complex issue. Moreover, at the same time, there is a consensus regarding key substances, the deficiency of which threatens to lead to poor nutrition. Let us consider the main groups of such substances, taking into account the prospects for their production both from aquaculture and alternative sources.

Quest for protein: animals, plants, or aquaculture?

Aquaculture can be considered as a source of supplying food markets with aquatic animals (including vertebrates, non-vertebrates, and plants), and as a source of full-fledged protein (Gómez et al. 2019; Al Khawli et al. 2020; Yaghubi et al. 2021).

However, a simple comparison of the available data (summarized in Table 1) shows that aquaculture-related food products do not have any uniqueness in this regard. Considering the quality of the protein, which has physiological significance and reflects the proportion of protein available to the body for plastic needs, the content of amino acids can vary significantly. The amino acid score is a measure of the ratio of a specific essential amino acid in a protein to the same amino acid in an ideal protein -

Table 1. Nutritional quality of protein of different origins

Protein source	Protein digestibility-corrected amino acid score (PDCAAS)	References
Egg	1.00	(Hoffman and Falvo 2004; Marinangeli and House 2027)
Beef	1.00	(Hoffman and Falvo 2004; Marinangeli and House 2027)
Chicken breast	1.00	(Marinangeli and House 2027)
Cod	0.96	(Sarwar et al. 1989)
Tuna	0.97	(Sarwar et al. 1989)
Salmon	1.00	(Usydus et al. 2009)
Rainbow trout	1.00	(El and Kavas 1996)
Northern shrimp	0.99	(Dayal et al. 2013)
Kamchatka crab	0.55	(Venugopal and Gopakumar 2017)
Karakatitsa Japanese	0.70	(Tahergorabi et al. 2011; Petricorena 2015)
Oysters	0.96	(Tahergorabi et al. 2011; Petricorena 2015)
Sea scallops of artificial breeding	0.70	(Tahergorabi et al. 2011; Petricorena 2015)
Soy	1.00	(Hughes et al. 2011)
Beans	0.07	(Sarwar et al. 1989)
Lentils	0.52	(Sarwar et al. 1989)
Peas	0.78	(Ertl et al. 2016)
Hemp seeds	0.97	(House et al. 2010)

a theoretical protein that is ideally balanced in amino acid composition (Boutrif 1991; Schaafsma 2000) and is a factor for the consideration of specific protein as relevant for human consumption. The protein scores of fish and clams are indeed very close to the standard beef scores. However, proteins from cultivated plants, in particular hemp and soybean, are also characterized by similar parameters (Dimina et al. 2021; Sui et al. 2021; Day et al. 2022; Qin et al. 2022). Soy proteins contain well-balanced essential amino acids except for sulfur-containing amino acids such as methionine (Qin et al. 2022), in addition, the values of the protein digestibility-adjusted amino acid score (PDCAAS) and the digestibility of essential amino acids (DIAAS) are relatively high, so they are considered as good quality proteins (Azizi et al. 2024). In addition, food science trends are directed towards combining plant proteins to obtain amino acid profiles adapted to different nutritional objectives (Dimina et al. 2021). Moreover, the modern biotechnological/microbiological industry allows not only to effectively solve the problems of enriching plant proteins with essential amino acid supplements but even to solve special problems by modifying the soy protein structure (Sui et al. 2021; Song et al. 2024).

It is important to keep in mind that both the economic and environmental costs associated with obtaining plant protein are immeasurably lower than the costs of obtaining protein from aquaculture. Based on publicly available data, we analyzed and compared the cost of aquatic and plant protein in terms of dry pure protein, and the data are presented in Table 2.

Comparative analysis shows that the availability of plant protein is significantly higher. This is determined by the essential differences between autotrophic and heterotrophic organisms, which, in turn, are determined by the laws of thermodynamics; in the classical food pyramid consisting of three trophic levels, plants, as primary producers, transfer energy to the organic matters, providing them to the consumers (Lindeman 1942).

The value of available protein from commercial wild fish is considerably less than that from artificially farmed fish. In agreement with the above, we undertake to argue that such a large gap in the cost-effectiveness of obtaining protein from aquatic organisms and plants is unlikely to be bridged by technological innovation. Moreover, we undertake to assert that such a significant gap in economic efficiency between obtaining protein from aquatic organisms and plants can hardly be overcome through technological innovation. However, commercialization must also consider the fact that wild fish have significant environmental importance, and this must be carefully considered.

Fatty acids: go green or go fish?

The correct ratio of fat components, especially polyunsaturated fatty acids or omega 3-6-9, is required for the full functioning of the human body. Omega-3 fatty acids are crucial in preventing cardiovascular diseases as they serve as an anti-arrhythmic, anti-inflammatory, anti-thrombotic, anti-atherosclerotic, anti-fibrotic, and endothelial relaxant. Additionally, they can improve in regards to the prevention and treatment of various conditions such as hypertriglyceridemia, hypertension, rheumatoid arthritis, asthma, lupus erythematosus, diabetes, migraines, nephritis, and psoriasis (Abbas et al. 2023). The mention of aquatic organisms as a source of unsaturated fatty acids has become commonplace in recent decades (Vyncke et al. 2012; Chen et al. 2022; Meyer et al. 2003; FAO/WHO 2024). Indeed, fish, mollusks, and arthropods are rich in these compounds and contain omega-3 and omega-6 fatty acids in the optimal ratio for human nutrition (Abd Aziz et al. 2013; Tan et al. 2020; Shao et al. 2023). Most of these essential substances for balanced nutrition can be provided to humans from plants (Monika and Anna 2019) or algae (Breuer et al. 2013; Sandgruber et al. 2021) origin food products. The biology of *Chlorella* sp. is developing intensively, this object has been perfectly developed technologically (Barkia et al. 2019; Bito et al. 2020; Je and Yamaoka 2022). It can be argued that there are no obstacles to launching powerful biosynthetic production of unsaturated fatty acids necessary for humans from *Chlorella* sp. The economics of microbial biosynthesis technologies, especially considering that in the case of *Chlorella*, autotrophic organisms are used, are comparable to those for crop production and, again, for thermodynamic reasons, are unattainable for aquaculture. In addition, the food industry is intensively developing technologies for producing

Table 2. The cost per unit of dry pure protein from aquatic organisms and plants

Product/ Protein source	Price of product, USD.kg^{-1}	Protein content, g.100 g^{-1}	Pure protein price, USD.kg^{-1}	References
Skipjack tuna	1.70	28.00	6.10	FAO (2024a)
Salmon	7.50	23.00	32.60	FAO (2024b); Tradingeconomics home page (2024)
Pangasius	3.00	17.20	17.40	FAO (2024c)
Tilapia	1,29	20.00	6,45	FAO (2024d)
Shrimp	5.00	30.00	16.60	Mordorintelligence home page (2024)
Soybeans	0.43	40.00	1.10	Tradingeconomics home page (2024)
Soy flour	0.48	49.00	0.98	Tridge - Global Food Sourcing & Data Hub home page (2024)
Soy isolate	2.21	90.00	2.40	Chemanalyst home page (2024)

new vegetable oils for mass consumption, such as flaxseed (Singh et al. 2011), which is increasingly used in feed for aquatic animals (Turchini et al. 2009).Until recently, it was considered that teleost fish, in particular, Atlantic cod (*Gadus morhua* L.), contain a unique complex of enzymes for the biosynthesis of these substances (Tocher et al. 2006; Xie et al. 2021). However, it turned out that several microorganisms, in particular microalgae *Nannochloropsis* sp. and *Thraustochytrids* (intermediate eukaryotic forms between algae and fungi), as well as fungi and bacteria also have similar metabolic pathways. Thus, the entire pool of unsaturated fatty acids can be obtained by industrial microbiology methods (Abbas et al. 2023).

Vitamins and vitamin-like compounds

The term "hydrobionts" refers to any organisms that live primarily in water. This includes a wide range of aquatic life forms, from microscopic algae and bacteria to larger plants and animals. Hydrobionts of different types in general are considered rich in vitamins of different classes (Mafra et al. 2023). However, the biotechnological industry has long mastered vitamin production, including some chemical identical or similar structures. In addition, the vitamin content in some aquacultures does not fully correspond to human nutritional needs.

In terms of water-soluble vitamins, aquatic animals are inferior to plants (Waagbø 2021); in addition, mass-consumed aquaculture products, as a rule, require heat treatment, which negatively affects the content of some key vitamins. At the same time, the most valuable carotenoids for the consumer are not synthesized by hydrobionts but enter the food chain from their microbial links (Meléndez-Martínez et al. 2022). It is well-known that the attractive red color of salmon meat is determined by the presence of carotenoid astaxanthin, which is synthesized by microscopic algae and fungi (Langi et al. 2018; Kumar et al. 2022). The deficiency of carotenoids in aquaculture salmon feeds has led to the practice of coloring salmon and other fish with synthetic and natural-derived dyes. Technologies for microbial synthesis of astaxanthin and other carotenoids are being intensively developed. This will lead to the improved cost-effectiveness of the existing products and the emergence of fundamentally new ones (Basiony et al. 2022). Thus, we can confidently predict the development of biotechnology of *Deinococcus radiodurans*, a bacterium that produces the carotenoid antioxidant deinoxanthin, which is more “powerful” than astaxanthin (Lysenko et al. 2011; Jeong et al. 2020; Sadowska-Bartosz and Bartosz 2023). Additionally, yeasts should be considered as biotechnological factories for the production of antioxidants that can be used as fish feed additives to improve the quality of fish meat (Barredo et al. 2017).

Probiotics "from farm to fork"

Over the past few decades, a lot of data has accumulated on research, *in vivo* testing and the introduction of probiotics into aquaculture practice (Sumon et al. 2022; Yousuf et al. 2023). However, efforts are aimed at solving the following problems: a) increasing the survival rate of fry, b) modulating the immune system, c) improving growth performance, and d) using probiotics as an alternative to antibiotics in the treatment and prevention of aquaculture diseases (Van Doan et al. 2019). Similar work is being carried out successfully in the areas of research and the use of probiotics for livestock and poultry farming. At the same time, studies are emerging aimed at a new direction in research, namely the use of probiotics to improve the quality of muscle tissues for the end consumer. For instance, it has been shown, that the use of pediococci probiotics in poultry may lead to higher short shain fatty acids (SCFA) meat content and improvement of the flavor (Wang et al. 2017). Similar results with higher SCFA meat content were achieved in poultry fed with bacilli probiotics (Neijat et al. 2019). Another study with the probiotic *Bacillus subtilis* in chicken reported achieving a combination of quality factors that improved meat parameters, such as lower cholesterol levels, improved water holding capacity and reduced cooking losses (Yang et al. 2016). Finally, studies conducted with a different strain of bacillary probiotic in chickens showed improvements in both quality and sensory parameters: an increase in protein and free amino acids, as well as a decrease in fat content; and improvement of color, taste, juiciness, and flavor (Liu et al. 2012). Regarding aquaculture, some studies indicate that, despite improvements in vital signs, there was no qualitative dietary improvement in the muscle tissue of fish (Ozorio et al. 2015). However, some authors have noted an increase in total protein in carcasses of fish fed with probiotic-containing feed (Azarin et al. 2014; Reda and Selim 2014). Finally, isolated publications indicate a possible improvement in the quality of muscle tissue of fish treated with probiotic strains, namely a decrease in oxidation and an increase in the amount of polyunsaturated fatty acids in the enzymatically processed product (Marzia et al. 2018). Antioxidant production by probiotic strains is known to perform a protective role by preventing the oxidation of lipids (Prazdnova et al. 2015; Zolotukhin et al. 2017; Mazanko et al. 2022; Prazdnova et al. 2022). Lipid oxidation can cause deterioration in fish quality, resulting in off-flavors, discoloration, negative changes in meat texture, etc. (Wu et al. 2022). In conclusion, although probiotics are now being seriously considered as nutritionally important components of fish feed and as a new generation of nutraceuticals for fish (Wuertz et al. 2021), very little has been reported on the possible role of probiotics in improving the quality characteristics of aquaculture products when it comes to modulating human health. Therefore, we can confidently say that new research is needed aimed at studying the capabilities of probiotics in improving the quality characteristics of fish products for the end consumer.

Modern biological science has made noticeable progress in understanding complex and important issues related to the organoleptic qualitative characteristics of food (Thavarajah and Thavarajah 2012). The prominent Japanese chemist Kikunae Ikeda discovered in 1908 that the chemical basis of meat taste (umami) is the presence of monosodium glutamate in food (Nakamura 2011). Since then, “flavor chemistry” excelled dramatically. It has become clear that the attractiveness of animal food to humans is determined, as a rule, by peptides, amino acids, and Maillard reaction products (Fogliano 2016). At the same time, it is not necessary to introduce synthetic compounds into the product to create taste.

Properly organized fermentation, in the case of Japanese miso, for example, allows to “cut” peptides from soy protein that mimic both meat and fish taste (Inoue et al. 2016; Li et al. 2020). Of course, the discerning taste of caviar and oyster sommeliers is unlikely to be deceived by fermentation products, but the mass consumer, given the overpopulation of the Earth and a general food shortage, will apparently be satisfied.

Thus, the goal of providing nutrition to growing humanity is much easier to achieve, both economically and ecologically, through the development of crop production in combination with food biotechnology and microbial synthesis. Consequently, the corresponding goal for aquaculture is somewhat questionable, and competition with an obviously stronger opponent is fraught with failure.

In economic terms, the transition from the production of large volumes of mass aquaculture products to the production of luxury products intended for "special occasion consumption" will not be troublesome if it is carried out consistently and planned. The realistic and achievable goal of the aquaculture industry should be to satisfy the need for gourmet food, that is, to provide people with a festive mood, and not a set of proteins, carbohydrates and vitamins. The cost of these products must correspond to their luxury quality. Reducing the production volumes of aquaculture facilities will reduce the load on the ecosystems involved in this technology, abandon unnecessary "chemicalization", and introduce a wide range of biological products, i.e. make aquaculture products truly organic. The use of probiotic preparations can significantly help in moving towards this goal. They will help improve the taste of fish and invertebrate meat, significantly reduce the use of synthetic preparations and improve the environmental condition of reservoirs used for aquaculture.

Conclusion

The evolution of human society, driven by technological and economic advancements, highlights the dynamic and often unpredictable nature of progress. To ensure harmonious development and avoid crises, continuous and objective analysis of trends in various industries, including aquaculture, is essential. Aquaculture, as defined by the FDA, involves the farming of aquatic organisms with interventions to improve health and production. It plays a crucial role in providing nutritious food for the growing global population and addressing food security. Aquaculture is a rapidly growing sector of protein supply, combining natural resources and farming practices to enhance yields and environmental sustainability. It offers high-quality protein, polyunsaturated fatty acids, omega-3, omega-6, and omega-9 fatty acids, vitamins, and minerals, which are vital for human health. Where the correct ratio of all elements is crucial for the proper functioning of the human body. Aquatic organisms, such as fish, mollusks and algae, are rich in essential fatty acids and provide them with optimal ratios for human nutrition. Biotechnological advancements in microbial biosynthesis, using some aquaculture, particularly *Chlorella* sp. or other microalgae or bacterial species in processes for biosynthesizing these essential fatty acids, make industrial microbiology a viable method for producing them. These methods are economically comparable to traditional crop production and have the potential to meet human nutritional needs without relying on aquaculture. Aquaculture can be considered the next frontier to provide a sustainable solution to meet the rising protein demand while having a lower environmental impact compared to traditional livestock farming . Moreover, aquaculture proteins are particularly important in regions with limited access to traditional protein sources, improving food security and addressing malnutrition. However, challenges such as contaminants in aquaculture products and dependency on fishmeal and fish oil must be addressed to fully realize its potential, where researchers are exploring alternative feed ingredients to reduce environmental impact and ensure sustainable production takes an important part. Overall, exploring aquaculture proteins is crucial for global food security and nutrition. Continued research and innovation in aquaculture practices and feed formulations will be key to achieving these goals and providing a reliable source of high-quality protein for the global population.

Acknowledgments

Authors acknowledge the support of the Russian Science Foundation grant No. 23-76-30006, https://rscf.ru/project/23-76-30006/. SDT was supported by FAPESP (Grant 2023/05394-9), Sao Paulo, SP, Brazil and FCT (UIDB/05937/2020 and UIDP/05937/2020), Fundação para a Ciência e a Tecnologia, Portugal

References

Abbas N., Riaz S., Mazhar S., Essa R., Maryam M., Saleem Y., Syed Q., Perveen I., Bukhari B., Ashfaq S., Abidi S.H. Microbial production of docosahexaenoic acid (DHA): Biosynthetic pathways, physical parameter optimization, and health benefits. *Archives of Microbiology*, 2023, 205(9): 321. https://doi.org/10.1007/s00203-023-03666-x

Abd Aziz N., Azlan A., Ismail A., Mohd Alinafiah S., Razman M.R. Quantitative determination of fatty acids in marine fish and shellfish from warm water of straits of malacca for nutraceutical purposes. *BioMed Research International*, 2013,12: 284329. https://doi.org/10.1155/2013/284329

Al Khawli F., Martí-Quijal F.J., Ferrer E., Ruiz M.J., Berrada H., Gavahian M., Barba F.J., de la Fuente B. Aquaculture and its by-products as a source of nutrients and bioactive compounds. *Advances in Food and Nutrition Research*, 2020, 92: 1-33. https://doi.org/10.1016/bs.afnr.2020.01.001

Arshad N., Samat N., Lee L.K. Insight into the regulation between nutritional benefits of aquaculture products and its consumption hazards: A global viewpoint. *Frontiers in Marine Science*, 2022, 9:925463. https://doi.org/10.3389/fmars.2022.925463

Azarin H., Aramli M.S., Imanpour M.R., Rajabpour M. Effect of a probiotic containing *Bacillus licheniformis* and *Bacillus subtilis* and ferroin solution on growth performance, body composition and haematological parameters in kutum (*Rutilus Frisii Kutum*) Fry. *Probiotics and Antimicrobial Proteins*, 2014, 7(1): 31-37. https://doi.org/10.1007/s12602-014-9180-4

Azizi R., Baggio A., Capuano E., Pellegrini N. Protein transition: Focus on protein quality in sustainable alternative sources. *Critical Reviews in Food Science and Nutrition,* 2024, 6:1-21. https://doi.org/10.1080/10408398.2024.2365339

Barkia I., Saari N., Manning S.R. Microalgae for high-value products towards human health and nutrition. *Marine Drugs*, 2019, 17(5): 304. https://doi.org/10.3390/md17050304

Barredo J., García-Estrada C., Kosalkova K., Barreiro C. Biosynthesis of astaxanthin as a main carotenoid in the heterobasidiomycetous yeast *Xanthophyllomyces dendrorhous. Journal of Fungi*, 2017, 3(3): 44. https://doi.org/10.3390/jof3030044

Basiony M., Ouyang L., Wang D., Yu J., Zhou L., Zhu M., Wang X., Feng J., Dai J., Shen Y., Zhang C., Hua Q., Yang X., Zhang L. Optimization of microbial cell factories for astaxanthin production: Biosynthesis and regulations, engineering strategies and fermentation optimization strategies. *Synthetic and Systems Biotechnology*, 2022, 7(2): 689-704. https://doi.org/10.1016/j.synbio.2022.01.002

Bito T., Okumura E., Fujishima M., Watanabe F. Potential of chlorella as a dietary supplement to promote human health. *Nutrients,* 2020, 12(9): 2524. https://doi.org/10.3390/nu12092524

Biris-Dorhoi E.S., Michiu D., Pop C.R., Rotar A.M., Tofana M., Pop O.L., Socaci S.A., Farcas A.C. Macroalgae-A Sustainable Source of Chemical Compounds with Biological Activities. *Nutrients*, 2020, 12(10): 3085. https://doi.org/10.3390/nu12103085

Boutrif E. Recent developments in protein quality evaluation. *Food*, *Nutrition and Agriculture*, 1991, 1(2/3): 36-40. Available at: https://www.fao.org/4/u5900t/u5900t07.htm

Boyd C.E., McNevin A.A., Davis R.P. The contribution of fisheries and aquaculture to the global protein supply. *Food Security*, 2022, 14: 805-827. https://doi.org/10.1007/s12571-021-01246-9

Breuer G., Evers W.A.C., Vree J.H. de; Kleinegris D.M.M., Martens D.E., Wijffels R.H., Lamers P.P. Analysis of fatty acid content and composition in microalgae. *Journal of Visualized Experiments*, 2013, 80(10): 50628. https://doi.org/10.3791/50628

Chemanalyst Home Page. Available at: https://www.chemanalyst.com/Pricing-data/soy-protein-isolate-1578 (accessed on 06 August 2024).

Chen J., Jayachandran M., Bai W., Xu B. A critical review on the health benefits of fish consumption and its bioactive constituents. *Food Chemistry,* 2022, 369(2): 130874. https://doi.org/10.1016/j.foodchem.2021.130874

Day L., Cakebread J.A., Loveday S.M. Food proteins from animals and plants: Differences in the nutritional and functional properties. *Trends in Food Science & Technology*, 2022, 119: 428-442. https://doi.org/10.1016/j.tifs.2021.12.020

Dayal J.S., Ponniah A.G., Khan H.I., Babu E.M., Ambasankar K., Vasagam K.K. Shrimps - a nutritional perspective. *Current Science,* 2013, 104(11): 1487-1491. https://www.jstor.org/stable/24092471

Dimina L., Rémond D., Huneau J.-F., Mariotti F. Combining plant proteins to achieve amino acid profiles adapted to various nutritional objectives - an exploratory analysis using linear programming. *Frontiers in Nutrition*, 2021, 8: 809685. https://doi.org/10.3389/fnut.2021.809685

El S.N., Kavas A. Determination of protein quality of rainbow trout (*Salmo irideus*) by *in vitro* protein digestibility-corrected amino acid score (PDCAAS). *Food Chemistry*, 1996, 55(3): 221-223. https://doi.org/10.1016/0308-8146(95)00111-5

Ertl P., Knaus W., Zollitsch W. An approach to including protein quality when assessing the net contribution of livestock to human food supply. *Animal,* 2016, 10(11): 1883-1889. https://doi.org/10.1017/S1751731116000902

FAO/WHO. 2024. FAO/WHO background document on the risks and benefits of fish consumption. In: *Food Safety and Quality Series* (FAO; WHO Eds). Series number No. 27, FAO/WHO, Rome, Italy. 2024, 508 p. eBook ISBN: 978-92-5-138944-7 https://doi.org/10.4060/cd1548en

FAO, Food and Agriculture Organization of the United Nations Home Page. 2024. Available at: https://www.fao.org/home/en/ (accessed on 06 August 2024).

FAO, Food and Agriculture Organization of the United Nations Home Page. 2024a. Available at: https://www.fao.org/in-action/globefish/species-analysis/tuna/en (accessed on 06 August 2024).

FAO, Food and Agriculture Organization of the United Nations Home Page. 2024b. Available at: https://www.fao.org/in-action/globefish/species-analysis/salmon/en (accessed on 06 August 2024).

FAO, Food and Agriculture Organization of the United Nations Home Page. 2024c. Available at: https://www.fao.org/in-action/globefish/species-analysis/pangasius/en (accessed on 06 August 2024).

FAO, Food and Agriculture Organization of the United Nations Home Page. 2024d. Available at: https://www.fao.org/in-action/globefish/species-analysis/tilapia/en (accessed on 06 August 2024).

FDA, US Food and Drug Administration Home Page. Aquacultured Seafood, 2023. Available at: https://www.fda.gov/food/seafood-guidance-documents-regulatory-information/aquacultured-seafood (accessed on 06 August 2024).

Fogliano V. The long story of the Maillard reaction: The beginning of the second century. *Food & Function*, 2016, 7(6): 2496-2497. https://doi.org/10.1039/c6fo90022d

Gómez B., Munekata P.E.S., Zhu Z., Barba F.J., Toldra F., Putnik P., Bursać Kovačević D., Lorenzo J.M. Challenges and opportunities regarding the use of alternative protein sources: Aquaculture and insects. *Advances in Food and Nutrition Research,* 2019, 89: 259-295. https://doi.org/10.1016/bs.afnr.2019.03.003

Hoffman J.R., Falvo M.J. Protein - which is best? *Journal of Sports Science & Medicine,* 2004, 3(3): 118-130. Available at: https://www.jssm.org/volume03/iss3/cap/jssm-03-118.pdf

House J.D., Neufeld J., Leson G. Evaluating the quality of protein from hemp seed (*Cannabis Sativa* L.) Products through the use of the protein digestibility - corrected amino acid score method. *Journal of Agriculture and Food Chemistry,* 2010, 58(22): 11801-11807. https://doi.org/10.1021/jf102636b

Hughes G.J., Ryan D.J., Mukherjea R., Schasteen C.S. Protein digestibility - corrected amino acid scores (PDCAAS) for soy protein isolates and concentrate: Criteria for evaluation. *Journal of Agriculture and Food Chemistry,* 2011, 59(23): 12707-12712. https://doi.org/10.1021/jf203220v

Inoue Y., Kato S., Saikusa M., Suzuki C., Otsubo Y., Tanaka Y., Watanabe H., Hayase F. Analysis of the cooked aroma and odorants that contribute to Umami aftertaste of soy miso (Japanese soybean paste). *Food Chemistry*, 2016, 213(12): 521-528. https://doi.org/10.1016/j.foodchem.2016.06.106

Je S., Yamaoka Y. Biotechnological approaches for biomass and lipid production using microalgae Chlorella and its future perspectives. *Journal of Microbiology and Biotechnology*, 2022, 32(11): 1357-1372. https://doi.org/10.4014/jmb.2209.09012

Jester B.W., Zhao H., Gewe M., Adame T., Perruzza L., Bolick D.T., Agosti J., Khuong N., Kuestner R., Gamble C., Cruickshank K., Ferrara J., Lim R., Paddock T., Brady C., Ertel S., Zhang M., Pollock A., Lee J., Xiong J., Tasch M., Saveria T., Doughty D., Marshall J., Carrieri D., Goetsch L., Dang J., Sanjaya N., Fletcher D., Martinez A., Kadis B., Sigmar K., Afreen E., Nguyen T., Randolph A., Taber A., Krzeszowski A., Robinett B., Volkin D.B., Grassi F., Guerrant R., Takeuchi R., Finrow B., Behnke C., Roberts J. Development of spirulina for the manufacture and oral delivery of protein therapeutics. Nature Biotechnology, 2022, 40(6): 956-964. https://doi.org/10.1038/s41587-022-01249-7 Erratum in: Nature Biotechnology, 2022, 40(6): 974. https://doi.org/10.1038/s41587-022-01323-0

Je S., Yamaoka Y. Biotechnological approaches for biomass and lipid production using microalgae *Chlorella* and its future perspectives. *Journal of Microbiology and Biotechnology*, 2022, 32(11): 1357-1372. https://doi.org/10.4014/jmb.2209.09012

Jeong S.W., Kim J.H., Kim J.W., Kim C.Y., Kim S.Y., Choi Y.J. Metabolic engineering of extremophilic bacterium *Deinococcus radiodurans* for the production of the novel carotenoid deinoxanthin. *Microorganisms*, 2020, 9(1): 44. https://doi.org/10.3390/microorganisms9010044

Khan B.M., Liu Y. Marine mollusks: Food with benefits. *Compressive Reviews in Food Science and Food Safety*, 2019, 18(2): 548-564. https://doi.org/10.1111/1541-4337.12429

Kumar S., Kumar R., Kumari A., Panwar A. Astaxanthin: A super antioxidant from microalgae and its therapeutic potential. *Journal of Basic Microbiology*, 2022, 62(9): 1064-1082. https://doi.org/10.1002/jobm.202100391

Langi P., Kiokias S., Varzakas T., Proestos C. Carotenoids: From plants to food and feed industries. *Methods in Molecular Biology,* 2018, 1842(8): 57-71. https://doi.org/10.1007/978-1-4939-8742-9_3

Li Q., Zhang L., Lametsch R. Current progress in kokumi-active peptides, evaluation and preparation methods: A review. *Critical Reviews in Food Science and Nutrition,* 2020, 62(5): 1230-1241. https://doi.org/10.1080/10408398.2020.1837726

Lindeman R.L. The trophic-dynamic aspect of ecology. *Ecology,* 1942, 23(4): 399-417. https://doi.org/10.2307/1930126

Liu X., Yan H., Lv L., Xu Q., Yin C., Zhang K., Wang P., Hu J. Growth performance and meat quality of broiler chickens supplemented with *Bacillus licheniformis* in drinking water. *Asian-Australasian Journal of Animal Sciences,* 2012, 25(5): 682-689. https://doi.org/10.5713/ajas.2011.11334

Lysenko V.S., Chistyakov V.A., Zimakov D.V., Soier V.G., Sazykina M.A., Sazykina M.I., Sazykin I.S., Krasnov V.P. Separation and mass spectrometry identification of carotenoid complex from radioresistant bacteria *Deinococcus radiodurans*. *Journal of Analytical Chemistry,* 2011, 66(13): 1281-1284. https://doi.org/10.1134/S1061934811130144

Mafra D., Kemp J.A. de V., Cardozo L., Borges N.A., Alvarenga L.K., Stenvinkel P. Consumption of fish in chronic kidney disease - a matter of depth. *Molecular Nutrition & Food Research,* 2023, 67(9): e2200859. https://doi.org/10.1002/mnfr.202200859

Marinangeli C.P., House J.D. Potential impact of the digestible indispensable amino acid score as a measure of protein quality on dietary regulations and health. *Nutrition Reviews,* 2017, 75(8): 658-667. https://doi.org/10.1093/nutrit/nux048

Marzia G., Gai F., Peiretti P.G., Ortoffi M.F., Lavermicocca P., Lonigro S.L., Valerio F., Cavallarin L. Quality of ready-to-eat swordfish fillets inoculated with *Lactobacillus paracasei* IMPC 2.1. *Journal of the Science of Food and Agriculture,* 2018, 99(1): 199-209. https://doi.org/10.1002/jsfa.9161

Mazanko M.S., Prazdnova E.V., Kulikov M.P., Maltseva T.A., Rudoy D.V., Chikindas M.L. Antioxidant and antimutagenic properties of probiotic lactobacilli determined using LUX-biosensors. *Enzyme and Microbial Technology,* 2022, 155: 109980. https://doi.org/10.1016/j.enzmictec.2021.109980

Meléndez-Martínez A.J., Mandić A.I., Bantis F., Böhm V., Borge G.I.A., Brnčić M., Bysted A., Cano M.P., Dias M.G., Elgersma A., Fikselová M., García-Alonso J., Giuffrida D., Gonçalves V.S.S., Hornero-Méndez D., Kljak K., Lavelli V., Manganaris G.A., Mapelli-Brahm P., Marounek M., Olmedilla-Alonso B., Periago-Castón M.J., Pintea A., Sheehan J.J., Tumbas Šaponjac V., Valšíková-Frey M., Meulebroek L.V., O'Brien N. A comprehensive review on carotenoids in foods and feeds: status quo, applications, patents, and research needs. *Critical Reviews in Food Science and Nutrition,* 2022, 62(8): 1999-2049. https://doi.org/10.1080/10408398.2020.1867959

Meyer B.J., Mann N.J., Lewis J.L., Milligan G.C., Sinclair A.J., Howe P.R.C. Dietary intakes and food sources of omega-6 and omega-3 polyunsaturated fatty acids. *Lipids,* 2003, 38(4): 391-398. https://doi.org/10.1007/s11745-003-1074-0

Monika M., Anna K.D. Nut oils and their dietetic and cosmetic significance: A review. *Journal of Oleo Science,* 2019, 68(2): 111-120. https://doi.org/10.5650/jos.ess18216

Mordorintelligence Home Page. Shrimp Market Size & Share Analysis - Growth Trends & Forecasts Up to 2030, 2024. Available at: https://www.mordorintelligence.com/industry-reports/shrimp-market

Nakamura E. One hundred years since the discovery of the "Umami" taste from seaweed broth by Kikunae Ikeda, who transcended his time. *Chemistry - An Asian Journal,* 2011, 6(7): 1659-1663. https://doi.org/10.1002/asia.201000899

Naylor R.L., Hardy R.W., Buschmann A.H., Bush S.R., Cao L., Klinger D.H., Little D.C., Lubchenco J., Shumway S.E., Troell M.A. 20-year retrospective review of global aquaculture. *Nature,* 2021, 591 (7851): 551-563. https://doi.org/10.1038/s41586-021-03308-6

Neijat M., Habtewold J., Shirley R.B., Welsher A., Barton J.C., Thiery P., Kiarie E.G. *Bacillus subtilis* strain DSM 29784 modulates the cecal microbiome, concentration of short-chain fatty acids, and apparent retention of dietary components in shaver white chickens during grower, developer, and laying phases. *Applied and Environmental Microbiology*, 2019, 85(14): e00402-19. https://doi.org/10.3382/ps/pez324

Ozorio R.O.A., Kopecka-Pilarczyk J., Gabriela M., Lochmann R., Santos R.V., Santos G.D., Weber B., Calheiros J., Ferraz-Arruda L., Vaz-Pires P., Gonçalves J. Dietary probiotic supplementation in juvenile rainbow trout (*Oncorhynchus mykiss*) reared under cage culture production: Effects on growth, fish welfare, flesh quality and intestinal microbiota. *Aquaculture Research,* 2015, 47(9): 2732-2747. https://doi.org/10.1111/are.12724

Pereira L., Cotas J., Gonçalves A.M. Seaweed proteins: A step towards sustainability? Nutrients, 2024, 16(8): 1123. https://doi.org/10.3390/nu16081123

Petricorena Z.C. Chemical Composition of Fish and Fishery Products. In: *Handbook of Food Chemistry*, (P.C.K. Cheung, B.M. Mehta Eds.); Springer. 2015, pp.: 403-435, eBook ISBN: 978-3-642-41609-5, https://doi.org/10.1007/978-3-642-41609-5_12-1

Prazdnova E., Mazanko M.S., Chistyakov V.A., Bogdanova A., Refeld A.G., Kharchenko E.Yu., Chikindas M.L. Antimutagenic activity as a criterion of potential probiotic properties. *Probiotics and Antimicrobial Proteins*, 2022, 14(6): 1094-1109. https://doi.org/10.1007/s12602-021-09870-9

Prazdnova E.V., Chistyakov V.A., Churilov M.N., Mazanko M.S., Bren A.B., Volski A., Chikindas M.L. DNA-protection and antioxidant properties of fermentates from *Bacillus amyloliquefaciens* B-1895 and *Bacillus subtilis* KATMIRA1933. *Letters in Applied Microbiology*, 2015, 61(6): 549-554. https://doi.org/10.1111/lam.12491

Qin P., Wang T., Luo Y. A review on plant - based proteins from soybean: Health benefits and soy product development. *Journal of Agriculture and Food Research*, 2022, 7(7): 100265. https://doi.org/10.1016/j.jafr.2021.100265

Reda R.M., Selim K.M. Evaluation of *Bacillus amyloliquefaciens* on the growth performance, intestinal morphology, hematology and body composition of Nile tilapia, *Oreochromis niloticus*. *Aquaculture International*, 2014, 23(1): 203-217. https://doi.org/10.1007/s10499-014-9809-z

Sadowska-Bartosz I., Bartosz G. Antioxidant defence of *Deinococcus radiodurans*: How does it contribute to extreme radiation resistance? *International Journal of Radiation Biology*, 2023, 99(12): 1803-1829. https://doi.org/10.1080/09553002.2023.2241895

Sandgruber F., Gielsdorf A., Baur A.C., Schenz B., Müller S.M., Schwerdtle T., Stangl G.I., Griehl C., Lorkowski S., Dawczynski C. Variability in macro- and micronutrients of 15 commercially available microalgae powders. *Marine Drugs*, 2021, 19(6): 310. https://doi.org/10.3390/md19060310

Sarwar G., Peace R.W., Botting H.G., Brul D. Digestibility of protein and amino acids in selected foods as determined by a rat balance method. *Plant Foods for Human Nutrition*, 1989, 39(1): 23-32. https://doi.org/10.1007/BF01092398

Schaafsma G. The protein digestibility - corrected amino acid score. *The Journal of Nutrition*, 2000, 130(7): 1865S-1867S. https://doi.org/10.1093/jn/130.7.1865S

Shao C., Su Y., Meng D., Li Y., Dong Y., Hao H., Ye H. Comprehensive metabolomic profiling of nutrients in fish and shrimp. *Food Chemistry*, 2023, 407(6): 135037. https://doi.org/10.1016/j.foodchem.2022.135037

Singh K.K., Mridula D., Rehal J., Barnwal P. Flaxseed: A potential source of food, feed and fiber. *Critical Reviews in Food Science and Nutrition*, 2011, 51(3): 210-222. https://doi.org/10.1080/10408390903537241

Song B., Luo T., Fan Y., Li M., Qiu Z., Tian Y., Shang Y., Ma C., Liu C., Cao Q., Peng Y., Xu P., Krishnan H.B., Wang Z., Zhang S., Liu S. Generation of new β-conglycinin-deficient soybean lines by editing the lincRNA *lincCG1* using the CRISPR/Cas9 system. *Journal of Agricultural and Food Chemistry*, 2024, 72(26): 15013-15026. https://doi.org/10.1021/acs.jafc.4c02269

Sui X., Zhang T., Jiang L.. Soy protein: Molecular structure revisited and recent advances in processing technologies. *Annual Review of Food Science and Technology*, 2021, 12(1): 119-147. https://doi.org/10.1146/annurev-food-062220-104405

Sumon A.A., Sumon T.A., Hussain A., Lee S.J., Jang W.J., Sharifuzzaman S.M., Brown C.L., Lee E.W., Hasan M.T. Single and multi-strain probiotics supplementation in commercially prominent finfish aquaculture: Review of the current knowledge. *Journal of Microbiology and Biotechnology*, 2022, 32(6): 681-698. https://doi.org/10.4014/jmb.2202.02032

Tahergorabi R., Hosseini S.V., Jaczynski J. Seafood Proteins. In: *Handook of Food Proteins* (G.O. Phillips, P.A. Williams Eds.). Handbook of Food Proteins, Woodhead Publishing. 2011, pp. 116-149, ISBN: 978-1-84569-758-7, https://doi.org/10.1533/9780857093639.116

Tan K., Ma H., Li S., Zheng H. Bivalves as future source of sustainable natural omega-3 polyunsaturated fatty acids. *Food Chemistry*, 2020, 311(6): 125907. https://doi.org/10.1016/j.foodchem.2019.125907

Temple N.J. A rational definition for functional foods: A perspective. *Frontiers in Nutrition*, 2022, 9: 957516. https://doi.org/10.3389/fnut.2022.957516

Tocher D.R., Zheng X., Schlechtriem C., Hastings N., Dick J.R., Teale A.J. Highly unsaturated fatty acid synthesis in marine fish: Cloning, functional characterization, and nutritional regulation of fatty acyl Δ6 desaturase of Atlantic cod (*Gadus morhua* L.). *Lipids*, 2006, 41(11): 1003-1016. https://doi.org/10.1007/s10126-009-9179-0

Thavarajah D., Thavarajah P. Evaluation of chickpea (*Cicer arietinum* L.) micronutrients composition:

Biofortifiation opportunities to combat global micronutrient malnutrition. *Food Research International*, 2012, 49(1): 99-104. https://doi.org/10.1016/j.foodres.2012.10.007

Tradingeconomics Home Page. Salmon, 2024. Available at: https://tradingeconomics.com/commodity/salmon

Tradingeconomics Home Page. Soybeans, 2024. Available at: https://tradingeconomics.com/commodity/soybeans

Tridge - Global Food Sourcing & Data Hub Home Page. Soy Flour, 2024. Available at: https://www.tridge.com

Turchini G.M., Torstensen B.E., Ng W.K. Fish oil replacement in finfish nutrition. *Reviews in Aquaculture*, 2009, 1(1): 10-57. https://doi.org/10.1111/j.1753-5131.2008.01001.x

Usydus Z., Szlinder-Richert J., Adamczyk M. Protein quality and amino acid profiles of fish products available in Poland. *Food Chemistry*, 2009, 112(1): 139-145. https://doi.org/10.1016/j.foodchem.2008.05.050

Van Doan H., Hoseinifar S.H., Ringø E., Ángeles Esteban M., Dadar M., Dawood M.A.O., Faggio C. Host-Associated probiotics: A key factor in sustainable aquaculture. *Reviews in Fisheries Science & Aquaculture*, 2019, 28(1): 16-42. https://doi.org/10.1080/23308249.2019.1643288

Venugopal V., Gopakumar K. Shellfish: Nutritive value, health benefits, and consumer safety. *Comprehensive Reviews in Food Science and Food Safety*, 2017, 16(6): 1219-1242. https://doi.org/10.1111/1541-4337.12312

Vyncke K.E., Libuda L., De Vriendt T., Moreno L.A., Van Winckel M., Manios Y., Gottrand F., Molnar D., Vanaelst B., Sjöström M., González-Gross M., Censi L., Widhalm K., Michels N., Gilbert C.C., Xatzis C., Cuenca García M., de Heredia F.P., De Henauw S., Huybrechts I. Dietary fatty acid intake, its food sources and determinants in European adolescents: The HELENA (Healthy Lifestyle in Europe by Nutrition in Adolescence) study. *British Journal of Nutrition*, 2012, 108(12): 2261-2273. https://doi.org/10.3945/an.113.005678

Waagbø R. Water-soluble vitamins in fish ontogeny. *Aquaculture Research*, 2010, 41(5): 733-744. https://doi.org/10.1111/j.1365-2109.2009.02223.x

Wang Y., Sun J., Zhong H., Li N., Xu H., Zhu Q., Liu Y. Effect of probiotics on the meat flavour and gut microbiota of chicken. *Scientific Reports*, 2017, 7(1): 6400. https://doi.org/10.1038/s41598-017-06677-z

Wu H., Richards M.P., Undeland I. Lipid oxidation and antioxidant delivery systems in muscle food. *Comprehensive Reviews in Food Science and Food Safety*, 2022, 21(2): 1275-1299. https://doi.org/10.1111/1541-4337.12890

Wuertz S., Schroeder A., Wanka K.M. Probiotics in fish nutrition - long-standing household remedy or native nutraceuticals? *Water*, 2021, 13(10): 1348. https://doi.org/10.3390/w13101348

Xie D., Chen C., Dong Y., You C., Wang S., Monroig Ó., Tocher D.R., Li Y. Regulation of long-chain polyunsaturated fatty acid biosynthesis in teleost fish. *Progress in Lipid Research*, 2021, 82(4): 101095. https://doi.org/10.1016/j.plipres.2021.101095

Yaghubi E., Carboni S., Snipe R.M.J., Shaw C.S., Fyfe J.J., Smith C.M., Kaur G., Tan S.Y., Hamilton D.L. Farmed mussels: A nutritive protein source, rich in omega-3 fatty acids, with a low environmental footprint. *Nutrients*, 2021, 13(4): 1124. https://doi.org/10.3390/nu13041124

Yang J., Qian K., Zhang W., Xu Y., Wu Y. Effects of chromium-enriched *Bacillus subtilis* KT260179 supplementation on chicken growth performance, plasma lipid parameters, tissue chromium levels, cecal bacterial composition and breast meat quality. *Lipids in Health and Disease*, 2016, 15(1): 188. https://doi.org/10.1186/s12944-016-0355-8

Yousuf S., Tyagi A., Singh R. Probiotic supplementation as an emerging alternative to chemical therapeutics in finfish aquaculture: A review. *Probiotics and Antimicrobial Proteins*, 2023, 15(5): 1151-1168. https://doi.org/10.1007/s12602-022-09971-z

Zimmermann A., Prieto-Vivas J.E., Voordeckers K., Bi C., Verstrepen K.J. Mutagenesis techniques for evolutionary engineering of microbes - exploiting CRISPR-Cas, oligonucleotides, recombinases, and polymerases. *Trends in Microbiology*, 2024, 2(9): 884-901. https://doi.org/10.1016/j.tim.2024.02.006

Zolotukhin P.V., Prazdnova E.V., Chistyakov V.A. Methods to assess the antioxidative properties of probiotics. *Probiotics and Antimicrobial Proteins*, 2017, 10(3): 589-599. https://doi.org/10.1007/s12602-017-9375-6

Xu S., Ng J., Zhang X., Bai H., Sun D. Adsorption and photocatalytic degradation of Acid Orange 7 over hydrothermally synthesized mesoporous TiO_2 nanotube. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 2011, 379(1-3): 169-175. https://doi.org/10.1016/j.colsurfa.2010.11.032