ISSN: 3062-3235
I-CRAFT AGRICULTURAL and FOOD TECHNOLOGIES

Nutritional Benefits and Health Risks of Seafood Consumption

Yesim OZOGUL[1[0000-0001-7769-9225]] and Fatih ÖZOĞUL[1,2[0000-0002-0655-0105]]

[1] Çukurova University, Faculty of Fisheries Department of Seafood Processing Technology, Adana, Turkey
[2] Çukurova University, Biotechnology Research Centre, Adana, Turkey
yozogul@cu.edu.tr

Abstract. Around the world, seafood especially fish is an important part of people's diets because of the presence of both macronutrients (proteins, lipids and ash) and micronutrients (vitamins and minerals). These are key nutrients that support general health and wellbeing. Numerous marine species, including fish, shellfish, and crustaceans, are distinguished by its particular nutritional characteristics. Many nutritionists and health experts support consuming more seafood because of its high-quality protein, low fats, and essential micronutrients like vitamin D, iodine, and selenium. The polyunsaturated omega-3 fatty acids found in seafood, especially EPA and DHA, are necessary for brain development, cardiovascular health, and inflammation reduction. In addition, their regular intake has been shown to help with weight control, cognitive development in children, and lowering the risk of high blood pressure, inflammatory and neurodegenerative diseases. Despite its benefits, seafood consumption also poses certain risks. Environmental contamination introduces hazardous compounds such as heavy metals, pesticides, polycyclic aromatic hydrocarbons (PAHs), and microplastics into marine ecosystems. These pollutants can accumulate in seafood and potentially threaten human health. This review discusses the benefits and risks of eating seafood and the main points to consider when choosing and consuming it.

Keywords: Seafood, Nutrition, Health Benefits, Health Risks.

1 Introduction

Concerns about nutrition may arise as the world's population grows, and fish is a significant source of animal protein. The rise globally in consumption of fish shows that the health benefits of its consumption are well-established both scientifically and nutritionally [1,2]. It also means that fisheries and aquaculture will continue to play a crucial role in meeting the global population's demand for animal protein, with aquaculture being the dominant supplier. However, in terms of their share of the total animal protein supply, Norway (22.6%), Portugal (20.6%), and Spain (18.0%) were the top three European countries that consumed fish and seafood, while Turkey (surprisingly) had the lowest consumption rate (3.2%, despite being the EU's largest producer of marine finfish aquaculture). [3].

Atherosclerosis, diabetes mellitus, stroke, coronary heart disease, and several kinds of cancer are among the causes of mortality that are unmistakably linked to dietary habits and lifestyle choices [4, 5]. With

https://doi.org/10.65888/icraft.3.1.12

regard to dietary habits, a proper balance of nutrient intake is essential for maintaining health and avoiding lifestyle-related diseases. Eating seafood offers a variety of nutrients, including protein, vitamins, minerals, and the polyunsaturated long chain omega-3 fatty acids EPA (eicosapentanoic acid) and DHA (docosahexaenoic acid). In general, seafood is high in protein and unsaturated fats, low in calories, low in saturated fats and cholesterol and rich in minerals. Nutrients especially DHA and EPA, vitamin D, vitamin B12, iron (Fe), calcium (Ca), zinc (Zn), phosphorus (P), selenium (Se), fluorine (F), iodine (I) are found in fish and other seafood and are linked to a number of positive health impacts [6].

Seafood, particularly fish, have more free amino acids, non-saturated fatty acids, less connective tissues, and higher enzyme activities than other muscle products [6]. Thus, seafoods are perishable products, resulting in quality deterioration, such as lipid oxidation, protein degradation, and changes in fish taste, texture, and odor [7, 8]. These factors lead to seafood having a limited shelf life, which lowers customer acceptance. Thus, these products need to be processed and preserved properly to preserve their quality and safety. Moreover, it can also pose health risks if contaminated seafood with harmful substances like heavy metals, bacteria, viruses, or toxins [9]. Consuming contaminated seafood may lead to foodborne illnesses, allergic reactions, or long-term health problems. This review discusses the nutritional benefits and potential risks of seafood consumption, along with key considerations for its selection and safe consumption.Subsequent paragraphs, however, are indented.

1.1 The Chemical Composition of Fish

Fish proximate composition is crucial for understanding their nutritional profile and serves as an indicator for evaluating their quality, physiological state, and nutritional status [10]. A considerable amount of work has been carried out about the chemical analyses of fish species such as protein, fat, moisture, and ash levels, which is important from a variety of perspectives for producers, customers, and scientists. Such a research helps to better understand physiological condition of fish, nutritional value as well as how to process and preserve it. Fish is mostly composed of 66%–81% moisture, 16%–21% protein, 1.2%–1.5% mineral, 0.2%–25% fat, and 0%–0.5% carbohydrate [11]. In general, carbohydrates and non-protein compounds are usually ignored during analysis, since they make up a little portion of wet mass, usually thought to be insignificant (<0.5%) [12]. Various factors, including eating behaviors, food composition, rate of feeding, sex, age, size, habitats, genetics, season, and migration, may influence the chemical composition of fish species [13].

1.2 Proteins

The protein levels of raw finfish flesh range from 17% to 22%. Fish proteins have a relatively high nutritional value due to their advantageous essential amino acid composition. All of the necessary amino acids, especially methionine and lysine, are abundant in fish proteins [14]. It contains less fat than red meat and offers easily digestible protein with high biological value that is essential for the body's growth and development, for the maintenance and repair of damaged tissues, and for the synthesis of hormones and enzymes needed for many body functions. Three different types of proteins are usually found in fish muscle: 30% to 35% of the total protein level is made up of sarcoplasmic or enzymatic proteins (globulin, albumin, and enzymes); 60% to 65% is made up of myofibrillar or contractile proteins (actin, tropomyosin, myosin, and actomyosin); and 3% to 5% is made up of stroma or connective tissue proteins (collagen) [15]. Fish muscles are more digestible than other animal proteins because they include lower quantities of connective tissue. Fish muscle also typically contains 10–40% more non-protein nitrogen than that of terrestrial animals. This nitrogen content includes amino acids, small peptides, trimethylamine oxide (TMAO), trimethylamine, creatine, creatinine, and nucleotides [16].

1.3 Lipid

Fat level of fish ranges from 0.2 to 25%. Marine fish are commonly classified according to the fat content of their fillets and grouped as lean (<2% fat), low fat (2%–4% fat), medium (4–8% fat), and high fat (> 8% fat) [17]. Lean fish, such as sole, typically have whitish flesh, whereas species with moderate fat content (e.g., cod, haddock, halibut, and pollock) display white to off-white flesh. In contrast, high-fat fish, including herring, sardine, anchovy, and salmon, generally is pigmented such as yellow, pink, or greyish [14]. Fish fat content varies greatly among species and is affected by a number of biotic and abiotic parameters, including season, water temperature, sex, location in body, pH, age salinity, reproductive cycle, type and quantity of food available [18, 10].

Seafood contain polyunsaturated fatty acids (PUFAs), especially EPA and DHA, which are essential for proper growth of children and also reduce the occurrence of cardiovascular disease [19]. It has been found that the concentration of EPA and DHA fatty acids is generally higher in case of marine fishes [20]. Fats also contribute to energy supply and help with adequate absorption of vitamins A, D, E, and K [21].

Many people are interested in omega-3 long-chain polyunsaturated fatty acids (PUFAs), or n-3 LC-PUFAs, because of their distinct structure and biological functions. Omega-3 fatty acids are essential and need to be taken from diet. Fatty acids such as alpha-linolenic acid (ALA) (18:3n-3) and linoleic acid (LA) (18:2n-6) are known as essential fatty acids since these substances cannot be generated by humans [22]. Due to their plant-based synthesis, LA and ALA are mostly present in high concentrations in plant-based foods. For instance, LA is abundant in a variety of seeds, nuts, and plant oils [23]. For the synthesis of additional PUFAs, such as arachidonic acid (AA) (C20:4, n-6), docosahexaenoic acid (DHA) (C22:6, n-3), and eicosapentaenoic acid (EPA) (C20:5, n-3), the essential fatty acids LA and ALA are required.

Long-chain omega-3 PUFAs are produced by a sequence of enzymatic processes that are part of the metabolic route for the production of omega-3 PUFAs from ALA to DHA (Figure 1). It is ALA that initiates this metabolic process. An essential function of the enzymes desaturase and elongase is to convert dietary fatty acids into EPA-DHA. Enzymes that are desaturase help add double bonds to the metabolic pathway, whereas those that are elongase help add carbon atoms. The conversion of ALA to stearidonic acid is aided by the extra double bond that desaturase enzymes contribute. To create eicosatetraenoic acid (20:4n-3), elongase enzymes then add two carbon atoms to stearidonic acid. Extended EPA produces docosapentaenoic acid (DPA, 22:5n-3), whereas desaturation of DPA produces DHA (22:6n-3) [24]. The human body can only convert ALA to DHA to a very little extent, and the conversion rate from EPA to DHA is very low less than 1% [5]. For the early development of the brain and eyes, DHA is essential [25]. The plant omega-3 polyunsaturated fatty acid ALA's primary functions include regulating the conversion of LA to AA and serving as a substrate for the production of EPA [23]. The main sources of EPA and DHA are marine fatty fish species such as mackerel, herring, anchovy, sardines [26]. Additionally, fortified foods are thought to be a rich source of omega-3 fatty acids [27].

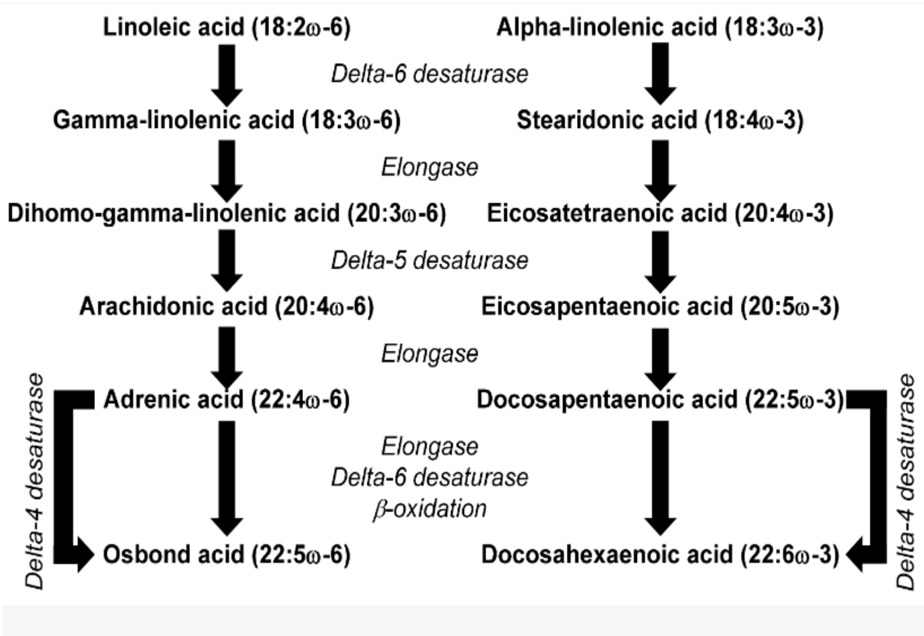

Fig.1. Metabolic pathway of omega-3 and omega 6 polyunsaturated fatty acids [24, 23].

1.4 Moisture

The moisture content of the majority of fish species typically ranges from 60% to 80%. Analyzing the moisture content of a fish is one of the first and most fundamental steps in determining the nutritional value of its complete body. Food's moisture content is a great way to determine how many calories, protein, and fat it contains. Fish with a lower moisture content is richer in fat and protein and has a greater density of calories [10]. According to [28], moisture content serves as a reliable indicator of the relative levels of energy, lipids, and proteins in fish, showing an inverse relationship with these parameters: the lower the water content, the higher the energy density and the greater the amounts of proteins and lipids.

1.5 Minerals

The detection of minerals in fish is linked to ash. Fish's mineral composition reflects their entire inorganic content, and the best way to determine it is to measure the fish's ash content first. The residue that remains after the fish sample has been completely ashed is called ash. After all of the organic material has been burned up, this inorganic residue is left behind. Ash level alters from 0.5% to 5% of total fish body weight [10]. Raw marine fish muscle and invertebrates contain between 0.6 to 1.5% wet weight of minerals such sodium, potassium, calcium, magnesium, and phosphorus, as well as microelements like selenium, fluorine, iodine, cobalt, manganese, and molybdenum [14]. According to [29], a variety of elements, including species, food, seasons, salinity, geographic location, and environmental factors including temperature, are in charge of causing changes in the mineral concentration of fish and shellfish. Furthermore, it is known that the minerals and trace elements that comprise the overall ash contents are influenced by a variety of other factors, including eating habits, the environment, migration ecology, and even the ability to thrive in the same habitat [30].

1.6 Vitamins

Vitamins provide essential organic components for enzymes catalyzing a number of metabolic reactions in the human body. Seafood and fish products have vitamins including vitamin D, vitamin A, vitamin C, vitamin E, vitamin B12, choline and folic acid [31]. Since many communities are concerned about vitamin D deficiency, eating fish can also help prevent symptoms like rickets and osteomalacia. Compared to meat or poultry, fish have a higher vitamin E concentration, which varies by species and tissue (dark muscle has higher levels). Depending on food, season, age, and size, the amount varies from 0.1 mg/100 g in certain wild fish species to 3–4 mg/100 g in cultured fish [32].

1.7 Health Benefits of Seafood Consumption

The beneficial effects of regular consumption of fish and seafood are supported by a significant number of studies. According to epidemiological research and clinical trials, consuming enough omega-3 fatty acids and maintaining a healthy ratio of omega-6 to omega-3 may lower the risk of blood pressure, inflammation, cardiovascular disease, and several forms of cancer (Figure 2). In addition to the beneficial effects of omega-3 fatty acids on the heart, their regular intake has been shown to help with weight control, cognitive development in children, and lowering the risk of high blood pressure, coronary heart disease, and stroke, as well as depression, and inflammatory diseases like rheumatoid arthritis [33, 34, 35]. In addition, Parkinson's disease and Alzheimer's disease are two types of neurodegenerative diseases associated with aging in the central nervous system. Numerous studies have shown that fish has a potential dietary therapy for the treatment of these diseases [36, 37, 38]. Omega-3 PUFAs (EPA + DHA) have promising effects on COVID-19 patients, according to recent data [39]. Accordingly, the Food and Agriculture Organization (FAO) of the United Nations (UN) and the World Health Organization (WHO) advise consuming one to two servings of seafood per week [40]. Specifically, the recommended daily intake of n-3 PUFAs varies by country and age group; it typically falls between 250 and 500 mg/day (equal to at least two servings of fish per week), and it is greater in newborns and pregnant and nursing women [41, 42].

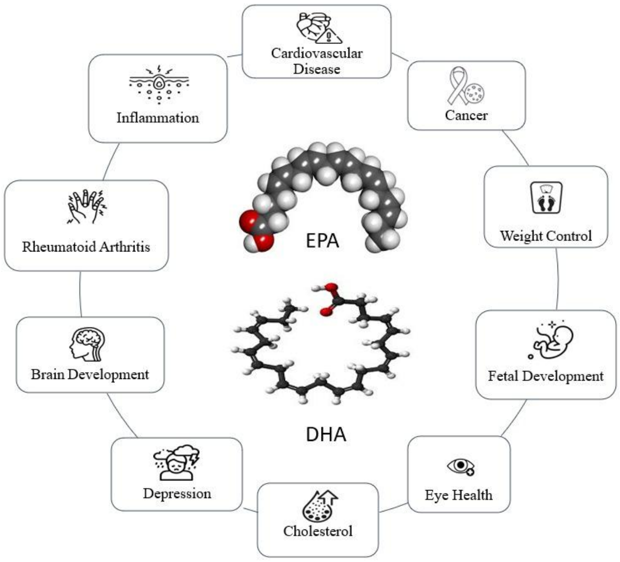

Fig. 2. The beneficial effects of regular consumption of omega 3 fatty acids.

1.8 Health Risks of Seafood Consumption

The health concerns of seafood must be taken into account despite their high nutritional content since they absorb pollutants and chemicals from their surroundings. Due to an increase in both natural and man-made activities, aquatic ecosystems have been continually subjected to heavy metal pollution in recent years [43]. Anthropogenic activities are generally acknowledged as the main contributors of heavy metals in aquatic systems. These activities include crop cultivation, erosion from agricultural areas, and the discharge of household and industrial trash. Heavy metals penetrate these systems, dissolve in the water, and easily build up in the organs of aquatic creatures, including fish, before entering the bodies of people who eat the contaminated fish [44]. Since very few trace metals are necessary for living things, these metals are divided into essential and non-essential categories. They can, however, be toxic to species at higher concentrations [45]. Toxic metals found in seafood, including copper (Co), cadmium (Cd), chromium (Cr), nickel (Ni), arsenic (As), lead (Pb), zinc (Zn), and mercury (Hg), can harm the human body by causing neurological disorders, kidney and liver damage, circulatory system issues, congenital abnormalities, immune system and reproductive system changes, and an increased risk of cancer [46, 47, 48, 49, 50]. A certain range of cellular concentrations of Cu, Mn, Fe, Zn, and Ni are necessary for regular human cellular processes. In the aquatic food chain, fish are at the top. Therefore, determining the levels of heavy metals in fish will not only help us comprehend the pollution caused by pollutants, but it will also help us identify the potential health risk that comes with eating finfish.

Another powerful contaminant in aquatic waterbodies is pesticides that are chemical compounds, either natural or synthetic, that are toxic in nature and commonly used to control various pests, insects, weeds, and pathogens to improve the yield quantity and quality. As a result, they have detrimental effects on aquatic organisms. The World Health Organization (WHO) divided pesticides into four groups based on their level of toxicity: extremely hazardous, highly hazardous, moderately hazardous, and slightly hazardous [51]. Around the world, a wide variety of pesticide groups, including insecticides, herbicides, bactericides, larvicides, and fungicides, are widely utilized. The primary source of pesticides in aquatic environments is agricultural runoff, which poses a major risk to aquatic animals and human health due to their accumulation in fish and hence destroy the food chain [52]. The sustainability of the environment and human health are both significantly impacted by the rising use of pesticides worldwide. The extensive use of pesticides contaminates the air, water, and soil, affecting ecosystem services and biodiversity. Furthermore, there are long-term health hazards associated with pesticide residues in food and the environment, including as cancer, endocrine disruption, neurological diseases, cognitive dysfunction, and cancer [53, 54].

In addition to pesticides, seafood has been reported to contain various industrial chemicals, including polychlorinated biphenyls (PCBs), used in electrical and hydraulic equipment, and polybrominated diphenyl ethers (PBDEs), employed as flame retardants in industrial and consumer products. Polycyclic aromatic hydrocarbons (PAHs), unlike purely anthropogenic contaminants, originate from both natural and human-related sources, arising as byproducts of incomplete combustion during industrial processes, vehicle emissions, and cooking methods such as grilling or smoking, as well as from natural events like wildfires [55].

Microplastics (MPs) with a diameter of less than 5 mm are produced when plastic trash breaks down through physical, chemical, and biological processes [56]. MPs, which are common in aquatic ecosystems, may be found in surface waters from the Arctic to Antarctica, as well as in beaches, deep sea sediments, and coastal sediments [57]. With the rise of plastic garbage, MPs have become a serious environmental issue. MPs have been shown in earlier research to have a variety of harmful impacts on aquatic organisms such as fish, benthic animals, zooplankton, phytoplankton [58, 59]. MPs have the ability to absorb dangerous contaminants from the environment, including pesticides, heavy metals, and persistent organic pollutants (POPs) [60]. The release of these toxins into the bodies of seafoods after ingestion can cause the toxins to bioaccumulate and biomagnify in the food chain. Because MPs may enter the human food chain through fish, there may be health problems, including developmental abnormalities, reproductive issues, and the risk of cancer [61]. The presence of MP in fresh and processed fish products from the German retail market was examined by Süssmann et al. [62]. 130 products in all, including canned, frozen, smoked, marinated, and fresh seafood, were examined. In seafood products, 97% of the MP found were less than 150 µm. Plastics were present in just 16% of the products under examination in quantities higher than those detectable by pyrolysis-gas chromatography-mass spectrometry, allowing for their identification and quantification. Polypropylene, polyethylene terephthalate, or polystyrene made up the identified MP. An estimated 16,500 particles of MP were consumed annually per person in Germany from seafood consumption. The highest MP contents were observed in both fresh and canned products. The study found a correlation between food contact materials and higher MP prevalence in seafood.

Biogenic amines (BAs) may pose a danger to people. They have low molecular weight, physiologically active substances and found naturally in a large range of foods. Bacterial activity or enzymatic activities aid in the decarboxylation of amino acids, which creates BAs in food products [63]. There are two amines among BA's that have the most toxic effects: histamine and tyramine. High histamine levels are observed in fish belonging to the Scombridae and Scomberesocidae families, such as mackerel, tuna, bonito, and bluefish etc. European Standard – Commission Regulation (EC) 1441/2007 applies only to fish products and allows histamine levels of 100–200 mg/kg in unprocessed fish [64]. The US Food and Drug Administration (FDA) recommends lower histamine levels of up to 50 mg/kg in fish and fish products [65]. The amount of histamine in food products is not subject to any particular regulations. "Scombroid poisoning" or "histamine poisoning" are terms used to describe the reaction to histamine toxicity. Tongue tingling, rash, vomiting, diarrhea, burning feeling, headache and lightheadedness, nausea, blood pressure decrease, vasodilation, cerebral bleeding, palpitations, or trouble breathing are the most typical signs of a high histamine consumption. The effects of histamine poisoning appear a few hours after histamine consumption, but may also manifest several days after consumption [66]. Consequently, monitoring and managing histamine content in seafood is crucial for ensuring both product quality and consumer safety.

To reduce the health risks associated with seafood consumption, the following points should be taken into consideration:

- Prefer seafood caught from clean and less polluted waters which greatly reduces the risk of heavy metal and microplastic contamination.
- Prefer farmed fish from certified sustainable aquaculture systems, which are subject to stricter monitoring of feed and water quality.
- Buy seafood from reliable sources that follow safety regulations and ensure that the seafood is fresh and have no off odor/flavor.
- Choose pelagic species (such as sardines, anchovies, or mackerel) since they generally accumulate fewer pollutants than bottom-dwelling fish.
- Diversify fish consumption by eating different species instead of relying on a single type which lowers the risk of long-term exposure to specific contaminants.
- Ensure proper handling, and maintain the cold chain during storage of seafood products to minimize microbial and chemical risks.
- Cook seafood thoroughly using methods such as steaming, baking, or grilling. This will eliminate harmful bacteria and parasites while minimizing the formation of PAHs.
- Stay updated on local authority about contamination levels in seafood and which species can be consumed in which season.
- Limit the consumption of raw or undercooked seafood (such as sushi, oysters, or clams) to reduce the risk of foodborne infections.
- To further reduce exposure, remove the skin and internal organs, which tend to accumulate certain pollutants.
- Pay attention to portion size and frequency when consuming seafood, and establish a balance between nutritional value and contamination risks.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

2 References

1. [1] Maulu, S., Nawanzi, K., Abdel-Tawwab, M., & Khalil, H. S. (2021). Fish nutritional value as an approach to children's nutrition. Frontiers in Nutrition, 8, 780844.

2. [2] Abera, B. D., & Adimas, M. A. (2024). Health benefits and health risks of contaminated fish consumption: Current research outputs, research approaches, and perspectives. Heliyon, 10(13).
3. [3] FAO. (2022). The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Rome. https://doi.org/10.4060/ cc0461en
4. [4] Gomez-Delgado, F., Katsiki, N., Lopez-Miranda, J., & Perez-Martinez, P. (2021). Dietary habits, lipoprotein metabolism and cardiovascular disease: From individual foods to dietary patterns. Critical reviews in food science and nutrition, 61(10), 1651-1669.
5. [5] Nestel, P. J., & Mori, T. A. (2022). Dietary patterns, dietary nutrients and cardiovascular disease. Reviews in cardiovascular medicine, 23(1), 17. nlm.nih.gov/pubmed/16188209, https://doi.org/10.1051/rnd:2005047.
6. [6] Rabiepour, A., Zahmatkesh, F., & Babakhani, A. (2024). Preservation techniques to increase the shelf life of seafood products: An overview. Journal of Food Engineering and Technology, 13(1), 1-24.
7. [7] Kontominas, M. G., Badeka, A. V., Kosma, I. S., & Nathanailides, C. I. (2021). Recent developments in seafood packaging technologies. Foods, 10(5), 940.
8. [8] Ozogul, Y. (2024). Methods for measuring seafood freshness quality and deterioration. In Handbook of Seafood and Seafood Products Analysis (pp. 198-230). CRC Press.
9. [9] Wu, L., Wu, T., Zeng, W., Tang, X., Zhang, L., Wang, C., & Zhang, L. (2024). Food Contaminants in Seafood. In Food Safety (pp. 99-117). CRC Press.
10. [10] Ahmed, I., Jan, K., Fatma, S., & Dawood, M. A. (2022). Muscle proximate composition of various food fish species and their nutritional significance: A review. Journal of Animal Physiology and Animal Nutrition, 106(3), 690-719.
11. [11] Love, R. M. (1970). The chemical biology of fishes. With a key to the chemical literature.
12. [12] Coppes Petricorena, Z. (2015). Chemical composition of fish and fishery products. In Handbook of food chemistry (pp. 403-435). Springer, Berlin, Heidelberg.
13. [13] Begum, M., Bhowmik, S., Juliana, F. M., & Hossain, M. S. (2016). Nutritional profile of hilsa fish [Tenualosa ilisha (Hamilton, 1822)] in six selected regions of Bangladesh. J. Nutr. Food Sci, 6(2), 567-570.
14. [14] Mohamed, H., & El Lahamy, A. A. (2020). Proximate chemical compositions and nutritional value of Fish. Journal of Current Research in Food Science, 1(2), 27-31.
15. [15] Nowsad, A. K. M. (2007). Participatory training of trainers, a new approach applied in fish processing. Bangladesh fisheries research forum, Mymensingh, Bangladesh, p. 329

16. [16] Hopkins, D., Holman, B., & Giteru, S. (2020). Total volatile basic nitrogen in meat products: occurrence, method of determination and use as a freshness indicator. https://doi.org/10.1016/j.plipres.2023.101255.
17. [17] Ackman, R. G. (1994). Seafood lipids. In Seafoods: Chemistry, processing technology and quality (pp. 34-48). Boston, MA: Springer US.
18. [18] Shirai, N., Suzuki, H., Tokairin, S., Ehara, H., & Wada, S. (2002). Dietary and seasonal effects on the dorsal meat lipid composition of Japanese (Silurus asotus) and Thai catfish (Clarias macrocephalus and hybrid Clarias macrocephalus and Clarias galipinus). Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 132(3), 609–619. https://doi.org/10.1016/S1095-6433(02)00081-8
19. [19] Tufail, T., Bader Ul Ain, H., Ashraf, J., Mahmood, S., Noreen, S., Ijaz, A., ... & Abdullahi, M. A. (2025). Bioactive Compounds in Seafood: Implications for Health and Nutrition. Food Science & Nutrition, 13(4), e70181.
20. [20] Swetha, N., & Mathanghi, S. K. (2024). Towards sustainable omega-3 fatty acids production–A comprehensive review on extraction methods, oxidative stability and bio-availability enhancement. Food Chemistry Advances, 4, 100603.
21. [21] Lall, S. P., & Dumas, A. (2022). Nutritional requirements of cultured fish: Formulating nutritionally adequate feeds. In Feed and feeding practices in aquaculture (pp. 65-132). Woodhead publishing.
22. [22] Khan, I., Hussain, M., Jiang, B., Zheng, L., Pan, Y., Hu, J., ... & Zou, X. (2023). Omega-3 long-chain polyunsaturated fatty acids: Metabolism and health implications. Progress in lipid research, 92, 101255.
23. [23] Djuricic, I., & Calder, P. C. (2021). Beneficial outcomes of omega-6 and omega-3 polyunsaturated fatty acids on human health: an update for 2021. Nutrients, 13(7), 2421.
24. [24] Bodur, M., Yilmaz, B., Ağagündüz, D., & Ozogul, Y. (2025). Immunomodulatory Effects of Omega-3 Fatty Acids: Mechanistic Insights and Health Implications. Molecular Nutrition & Food Research, 69(10), e202400752.
25. [25] Sinclair, A. J., Wang, Y., & Li, D. (2022). What is the evidence for dietary-induced DHA deficiency in human brains? Nutrients, 15(1), 161.
26. [26] Romanić, S. H., Jovanović, G., Mustać, B., Stojanović-Đinović, J., Stojić, A., Čadež, T., & Popović, A. (2021). Fatty acids, persistent organic pollutants, and trace elements in small pelagic fish from the eastern Mediterranean Sea. Marine pollution bulletin, 170, 112654.
27. [27] Patel, A., Desai, S. S., Mane, V. K., Enman, J., Rova, U., Christakopoulos, P., & Matsakas, L. (2022). Futuristic food fortification with a balanced ratio of dietary ω-3/ω-6 omega fatty acids for the prevention of lifestyle diseases. Trends Food Sci. Technol, 120(3), 140-153.

28. [28] Aberoumad, A., & Pourshafi, K. (2010). Chemical and proximate composition properties of different fish species obtained from Iran. World Journal of Fish and Marine Sciences, 2(3), 237–239.
29. [29] Rahman, M. M., Hajar, S., & Yunus, K. B. (2020). Comparative analysis of chemical composition of some commercially important fishes with an emphasis on various Malaysian diets. Open Chemistry, 18(1), 1323-1333.
30. [30] Hardy, R. W., & Kaushik, S. J. (Eds.). (2021). Fish nutrition. Academic press.
31. [31] Tacon, A. G. (2023). Contribution of fish and seafood to global food and feed supply: An analysis of the FAO food balance sheet for 2019. Reviews in Fisheries Science & Aquaculture, 31(2), 274-283.
32. [32] Afonso, C.; Bandarra, N.M.; Nunes, L.; Cardoso, C. Tocopherols in Seafood and Aquaculture Products. Crit. Rev. Food Sci. Nutr. 2016, 56, 128–140.
33. [33] Salman, H. B., Salman, M. A., & Akal, E. Y. (2022). The effect of omega-3 fatty acid supplementation on weight loss and cognitive function in overweight or obese individuals on weight-loss diet. Nutr Hosp, 39(4), 803-813.
34. [34] Sherzai, D., Moness, R., Sherzai, S., & Sherzai, A. (2023). A systematic review of omega-3 fatty acid consumption and cognitive outcomes in neurodevelopment. American Journal of Lifestyle Medicine, 17(5), 649-685.
35. [35] Serefko, A., Jach, M. E., Pietraszuk, M., Świąder, M., Świąder, K., & Szopa, A. (2024). Omega-3 polyunsaturated fatty acids in depression. International Journal of Molecular Sciences, 25(16), 8675.
36. [36] Li, P., & Song, C. (2022). Potential treatment of Parkinson's disease with omega-3 polyunsaturated fatty acids. Nutritional neuroscience, 25(1), 180-191.
37. [37] Ramírez-Higuera, A., Peña-Montes, C., Barroso-Hernández, A., López-Franco, Ó., & Oliart-Ros, R. M. (2023). Omega-3 polyunsaturated fatty acids and its use in Parkinson's disease. In Treatments, nutraceuticals, supplements, and herbal medicine in neurological disorders (pp. 675-702). Academic Press.
38. [38] Yelken, H. D., Elci, M. P., Turker, P. F., & Demirkaya, S. (2024). Omega fatty acid ratios and neurodegeneration in a healthy environment. Prostaglandins & Other Lipid Mediators, 170, 106799.
39. [39] Yang, C. P., Chang, C. M., Yang, C. C., Pariante, C. M., & Su, K. P. (2022). Long COVID and long chain fatty acids (LCFAs): Psychoneuroimmunity implication of omega-3 LCFAs in delayed consequences of COVID-19. Brain, Behavior, and Immunity, 103, 19-27.
40. [40] FAO & WHO. 2019. Sustainable healthy diets: Guiding principles. Rome. (also available at http://www.fao.org/3/ca6640en/ca6640en.pdf).

41. [41] EFSA Panel on Dietetic Products, Nutrition, and Allergies (NDA). (2010). Scientific opinion on dietary reference values for fats, including saturated fatty acids, polyunsaturated fatty acids, monounsaturated fatty acids, trans fatty acids, and cholesterol. Efsa Journal, 8(3), 1461.

42. [42] Van Dael, P. (2021). Role of n-3 long-chain polyunsaturated fatty acids in human nutrition and health: Review of recent studies and recommendations. Nutrition research and practice, 15(2), 137-159.

43. [43] Pandion, K., Khalith, S. M., Ravindran, B., Chandrasekaran, M., Rajagopal, R., Alfarhan, A., ... & Arunachalam, K. D. (2022). Potential health risk caused by heavy metal associated with seafood consumption around coastal area. Environmental pollution, 294, 118553.

44. [44] Ray, S., & Vashishth, R. (2024). From water to plate: Reviewing the bioaccumulation of heavy metals in fish and unraveling human health risks in the food chain. Emerging Contaminants, 10(4), 100358.

45. [45] Elbeshti, R. T., Elderwish, N. M., Abdelali, K. M., & Taştan, Y. (2018). Effects of Heavy Metals on Fish. Menba Journal of Fisheries Faculty., Vol: 4, İssue:1, Page:36-47.

46. [46] WHO (2006). Elemental Speciation in Human Health Risk Assessment; WHO: Geneva, Switzerland, 2006

47. [47] Varol, M., Kaya, G. K., & Sünbül, M. R. (2019). Evaluation of health risks from exposure to arsenic and heavy metals through consumption of ten fish species. Environmental Science and Pollution Research, 26(32), 33311-33320.

48. [48] Tanhan, P., Lansubsakul, N., Phaochoosak, N., Sirinupong, P., Yeesin, P., & Imsilp, K. (2022). Human health risk assessment of heavy metal concentration in seafood collected from Pattani Bay, Thailand. Toxics, 11(1), 18.

49. [49] Zaghloul, G. Y., Eissa, H. A., Zaghloul, A. Y., Kelany, M. S., Hamed, M. A., & Moselhy, K. M. E. (2024). Impact of some heavy metal accumulation in different organs on fish quality from Bardawil Lake and human health risks assessment. Geochemical Transactions, 25(1), 1.

50. [50] Singh, G., & Sharma, S. (2024). Heavy metal contamination in fish: sources, mechanisms and consequences. Aquatic Sciences, 86(4), 107.

51. [51] WHO (2019). The WHO Recommended Classification of Pesticides by Hazard and Guidelines to Classification

52. [52] Ghafarifarsani, H., Rohani, M. F., Raeeszadeh, M., Ahani, S., Yousefi, M., Talebi, M., & Hossain, M. S. (2024). Pesticides and heavy metal toxicity in fish and possible remediation–a review. Annals of Animal Science, 24(4), 1007-1024.

53. [53] Burch, E., Hussein, M. A., Zaki, M., Kamal, L. T., Zaki, G., Shoeib, T., ... & Abdelnaser, A. (2025). Assessing the Effects of Pesticides on Aquacultured Fish and Ecosystems: A Comprehensive Environmental Health Review. Fishes, 10(5), 223.
54. [54] Zhou, W., Li, M., & Achal, V. (2025). A comprehensive review on environmental and human health impacts of chemical pesticide usage. Emerging Contaminants, 11(1), 100410.
55. [55] Bedi, M., Sapozhnikova, Y., & Ng, C. (2024). Evaluating contamination of seafood purchased from US retail stores by persistent environmental pollutants, pesticides and veterinary drugs. Food Additives & Contaminants: Part A, 41(3), 325-338.
56. [56] Prata, J. C., Da Costa, J. P., Lopes, I., Duarte, A. C., & Rocha-Santos, T. (2020). Environmental exposure to microplastics: An overview on possible human health effects. Science of the total environment, 702, 134455.
57. [57] Karbalaei, S., Hanachi, P., Walker, T. R., & Cole, M. (2018). Occurrence, sources, human health impacts and mitigation of microplastic pollution. Environmental science and pollution research, 25(36), 36046-36063.
58. [58] Ali, N., Khan, M. H., Ali, M., Ahmad, S., Khan, A., Nabi, G., ... & Kyzas, G. Z. (2024). Insight into microplastics in the aquatic ecosystem: Properties, sources, threats and mitigation strategies. Science of the Total Environment, 913, 169489.
59. [59] Li, Y., Ling, W., Hou, C., Yang, J., Xing, Y., Lu, Q., ... & Gao, Z. (2025). Global distribution characteristics and ecological risk assessment of microplastics in aquatic organisms based on meta-analysis. Journal of Hazardous Materials, 137977.
60. [60] Debnath, R., Prasad, G. S., Amin, A., Malik, M. M., Ahmad, I., Abubakr, A., ... & Faggio, C. (2024). Understanding and addressing microplastic pollution: Impacts, mitigation, and future perspectives. Journal of Contaminant Hydrology, 266, 104399.
61. [61] Segovia-Mendoza, M., Nava-Castro, K. E., Palacios-Arreola, M. I., Garay-Canales, C., & Morales-Montor, J. (2020). How microplastic components influence the immune system and impact on children health: Focus on cancer. Birth defects research, 112(17), 1341-1361.
62. [62] Süssmann, J., Krause, T., Fischer, E. K., Walz, E., Greiner, R., Rohn, S., & Fritsche, J. (2025). Microplastics in fresh and processed seafood–A survey of products sold in Germany. Food Control, 111565.
63. [63] Özogul, Y., & Özogul, F. (2019). Biogenic amines formation, toxicity, regulations in food.
64. [64] Reinholds, I., Rusko, J., Pugajeva, I., Berzina, Z., Jansons, M., Kirilina-Gutmane, O., ... & Bartkevics, V. (2020). The occurrence and dietary exposure assessment of mycotoxins, biogenic amines, and heavy metals in mould-ripened blue cheeses. Foods, 9(1), 93.

65. [65] Ly, D., Mayrhofer, S., Schmidt, J. M., Zitz, U., & Domig, K. J. (2020). Biogenic amine contents and microbial characteristics of Cambodian fermented foods. Foods, 9(2), 198.
66. [66] EFSA Panel on Biological Hazards (BIOHAZ). (2011). Scientific opinion on risk based control of biogenic amine formation in fermented foods. Efsa Journal, 9(10), 2393.