

Fish-Based Fortification: A Promising Approach to Reduce Nutritional Deficiencies

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Abstract

Micronutrient deficiencies, or “hidden hunger,” remain a major global public health concern, particularly in low- and middle-income countries where diets are often energy-dense but nutrient-poor. Food fortification has emerged as an effective, sustainable strategy to address widespread deficiencies of iron, zinc, vitamin A, iodine, and other essential nutrients. Within this framework, fish and fish-derived products offer a unique opportunity for improving nutritional quality due to their naturally high bioavailability of proteins, omega-3 fatty acids, vitamins, minerals, and antioxidants. This review highlights the role of fish as a functional ingredient in fortification programs and examines key fish-based fortificants, including Fish Protein Concentrates (FPC), Fish Protein Hydrolysates (FPH), fish oil, and fish bone-derived calcium. Evidence shows that these ingredients not only enhance the nutrient density of food products but also improve health outcomes related to malnutrition, inflammation, cognitive development, and bone health. Several fortified food applications—such as snacks, bakery products, dairy items, and beverages—demonstrate the versatility of fish-derived components in population-wide nutrition interventions. By utilizing underused fish species and by-products, fish-based fortification also supports sustainable resource use. Overall, fish-derived fortification represents a viable and impactful approach to addressing multiple micronutrient deficiencies simultaneously while contributing to global food and nutrition security.

Keywords: Micronutrient, Fish Protein Concentrate (FPC), Fish Protein Hydrolysate (FPH), omega-3 fatty acids; fish oil; fish calcium; biofortification, malnutrition.

Introduction

Micronutrient deficiencies remain one of the most pressing public health challenges in low- and middle-income countries (LMICs). A lack of essential nutrients such as iron, zinc, and vitamin A has far-reaching effects on both physical growth and cognitive performance, particularly among vulnerable groups such as women and children. This problem, often referred to as hidden hunger, affects millions of people whose diets are dominated by calorie-rich but nutrient-poor foods (Muthayya *et al.*, 2013). Evidence suggests that micronutrient deficiencies contribute significantly to the global disease burden, accounting for nearly 7.3% of total disability-adjusted life years (DALYs) worldwide. In fact, deficiencies in iron and vitamin A rank among the top 15 causes of disease burden globally, and together they are responsible for the deaths of more than one million children every year (Black *et al.*, 2013).

Maternal and child malnutrition is of particular concern, as it is estimated to contribute to 45% of all deaths among children under five in LMICs (WHO, 2020). The World Health Organization (WHO) reports that approximately 42% of children under five and 40% of pregnant women worldwide are anaemic, largely due to iron deficiency. Women suffering from severe anemia during pregnancy face a twofold higher risk of death during or immediately after childbirth compared to non-anaemic women. For infants, inadequate maternal nutrition often results in low birth weight, impaired brain development, and congenital disorders such as neural tube defects (WHO, 2021).

Several factors contribute to micronutrient deficiencies, including poor dietary diversity, limited access to nutrient-rich foods, frequent infections, and physiological conditions such as blood loss during menstruation in women of reproductive age (Bailey *et al.*, 2015). The demand for micronutrients is especially elevated during pregnancy, lactation, and early childhood, making these life stages particularly vulnerable to nutritional inadequacies. To address these challenges, international organizations such as the WHO and the Food and Agriculture Organization (FAO) have emphasized four complementary strategies: food fortification, supplementation, nutrition education, and disease control (FAO and WHO, 2019). Among these, food fortification has emerged as a sustainable, cost-effective, and population-wide approach for reducing hidden hunger.

What Is Food Fortification?

Food fortification refers to the intentional addition of vitamins and minerals to commonly consumed foods during processing to improve their nutritional quality. It is regarded as one of the most practical and affordable public health measures for addressing micronutrient deficiencies (Poniedziałek, Perkowska, and Rzymiski, 2020). Because fortification targets staple foods that are widely consumed, it ensures consistent delivery of essential nutrients without requiring major changes in eating habits.

Types of Food Fortification

1. Large -Scale Food Fortification (LSFF)

LSFF is the most common form of fortification, in which nutrients are added to staple foods such as salt, wheat flour, rice, edible oils, sugar, and condiments during industrial processing. These programs may be either mandatory, led and regulated by governments, or voluntary, carried out by private food producers within regulatory frameworks (Mannar and Hurrell, 2018). One of the most successful examples is universal salt iodization, introduced in the early 1990s, which has dramatically reduced iodine deficiency disorders worldwide. Similarly, fortification of wheat flour with folic acid, initiated in 1942, is now mandatory in more than 85 countries, helping to prevent neural tube defects (Pachón *et al.*, 2015). Sugar fortification with vitamin A, first introduced in Latin America in the 1970s, is another widely adopted measure.

2. Biofortification

Unlike LSFF, which enriches food after harvest, biofortification improves the nutritional profile of crops while they are being grown. This is achieved either through traditional plant breeding techniques or agronomic practices such as mineral fertilization. Biofortification projects primarily focus on increasing levels of iron, zinc, and provitamin A carotenoids in staple crops like rice, beans, maize,

wheat, sweet potatoes, and cassava (Bouis and Saltzman, 2017). For instance, orange-fleshed sweet potatoes biofortified with vitamin A have been successfully introduced in parts of Africa, significantly reducing vitamin A deficiency among children.

3.Point of use (Home) Fortification

Point-of-use fortification involves the addition of micronutrients directly to foods that are already prepared and ready to eat. The most common form is the use of micronutrient powders (MNPs), which are typically added to complementary foods for infants and young children. Recognizing its effectiveness, the WHO in 2016 recommended point-of-use fortification as a key strategy to improve iron status and reduce anemia in children aged 6–24 months (WHO, 2016). This approach has also been widely implemented in schools, refugee camps, and other community-based settings.

Mandatory Fortification

This type of fortification is implemented by the government to ensure that large sections of the population receive essential nutrients through everyday food items. By making it compulsory, the aim is to tackle widespread nutrient deficiencies and improve overall public health. Common examples include adding iodine to salt, folic acid to flour, vitamin D to milk, niacin to bread, and fluoride to drinking water.

Voluntary Fortification

In this case, food manufacturers themselves decide to enrich their products with additional vitamins or minerals. This is often done to meet consumer preferences for healthier options or as part of a marketing strategy to make their products more appealing. Examples can be seen in fortified breakfast cereals, energy drinks, and other processed foods.

The Need for Fortification

Although a balanced diet is the foundation of good health, studies have shown that many populations fail to meet their daily nutrient requirements. Factors such as affordability, taste preferences, cultural beliefs, limited availability of nutrient-dense foods, and lack of cooking knowledge often restrict healthy eating (Christenson, O’Kane, Farmery, and McManus, 2017). According to the Food and Agriculture Organization (FAO, 2022), diets rich in essential nutrients play a crucial role in preventing diet-related illnesses, far more effectively than energy-dense but nutrient-poor alternatives.

This issue is most evident in low-income groups, where unhealthy processed foods are more affordable and accessible compared to healthier options. Such dietary patterns are strongly linked to non-communicable diseases (NCDs) associated with excessive intake of refined carbohydrates, fats, and salt (Hawkes, Ruel, Salm, Sinclair, and Branca, 2020).

Furthermore, rapid urbanization, rising household incomes, and fast-paced lifestyles have significantly transformed global eating habits. The growing preference for convenience foods, while contributing to unhealthy diets, also presents an opportunity. By fortifying these widely consumed products, governments and industries can help bridge nutritional gaps and promote better health outcomes in modern societies.

Fish as a Functional Food Ingredient

Within the framework of food fortification, fish is widely recognized as an excellent functional food ingredient. It provides an affordable source of protein, particularly in developing countries where access to diverse foods is often limited (Béné *et al.*, 2015). According to the FAO (2022), aquatic foods accounted for around 7% of the global average protein supply in 2019, underlining their nutritional significance.

What makes fish especially suitable for fortification is its unique nutritional profile. It contains high-quality proteins, long-chain omega-3 fatty acids, essential vitamins and minerals, and various antioxidants, all of which contribute to improved health outcomes. The European Food Safety Authority (EFSA) has recommended regular seafood consumption- one to two servings weekly for the general population, and three to four servings weekly during pregnancy - because of its role in supporting brain development in children and lowering the risk of cardiovascular-related mortality in adults (EFSA, 2014).

Furthermore, research by Hicks *et al.* (2019) highlighted that nutrients available from local fish catches could substantially cover the dietary requirements of populations living within 100 km of coastal zones in countries where micronutrient deficiencies are widespread. This demonstrates the vital role fish can play not only as a dietary staple but also as a strategic food for improving nutritional security through fortification.

Fish-Based Fortification

Fish-based fortification presents several advantages when compared to conventional fortification strategies. Unlike single-nutrient fortification, fish naturally contains a wide spectrum of essential nutrients within one source, making it a highly efficient option for improving dietary quality (Table 1). Its rich nutritional profile allows it to tackle multiple deficiencies simultaneously, an important benefit for populations where several micronutrient gaps coexist.

A key feature of fish as a fortificant is the high bioavailability of many of its nutrients. For example, long-chain omega-3 fatty acids, calcium, and trace minerals from fish are absorbed and utilized more effectively than those from many plant-based or synthetic sources. This makes fish-derived fortification not only nutrient-dense but also biologically efficient.

Several fish-based products have been identified for use in fortification programs. These include Fish Protein Concentrates (FPC), which serve as a concentrated source of high-quality protein; Fish Protein Hydrolysates (FPH), which provide easily digestible peptides and amino acids; fish oil, rich in omega-3 fatty acids; and fish-derived calcium, obtained from bones, which serves as a sustainable mineral source. Each of these products offers unique nutritional and functional benefits, making them suitable for incorporation into a variety of foods aimed at addressing malnutrition.

Table 1. Benefit of fish component

Nutrient	Component	Function / Health Benefit	Reference
Protein	(Sarcoplasmic, Myofibrillar, Stroma)	Provides all essential amino acids needed for muscle repair, growth, and overall body functions	Chalamaiah, Kumar, Hemalatha, and Jyothirmayi, 2012
Omega-3 Fatty Acids	(EPA Eicosapentaenoic Acid)	– Reduces inflammation, lowers risk of heart disease, decreases triglyceride levels, supports blood pressure control, prevents clot formation	Calder, 2017
Omega-3 Fatty Acids	(DHA Docosahexaenoic Acid)	– Essential for brain development, improves vision, enhances cognitive performance	Yurko-Mauro et al., 2010
	Vitamin D	Promotes bone health, supports immune function, reduces inflammation	Holick, 2007
	Vitamin B12	Important for nerve function, DNA synthesis, and red blood cell formation	Stabler, 2013
	Iodine	Required for thyroid hormone production and metabolic regulation	Zimmermann, 2009
	Selenium	Acts as an antioxidant, aids thyroid function, and supports immune defense	Rayman, 2012
	Calcium	Strengthens bones, maintains muscle function, and supports nerve signaling	Weaver, 2014
	Astaxanthin (Antioxidant)	Neutralizes free radicals, protects cells, lowers risk of chronic diseases, and promotes overall health	Guerin, Huntley, and Olaizola, 2003

Fish Protein Concentrate (FPC) or Fish Powder

Fish Protein Concentrate (FPC), commonly referred to as fish powder, is a processed fish product with a significantly higher protein concentration compared to the raw fish from which it is derived (Kumoro *et al.*, 2022). Produced in powdered form, FPC is prepared by carefully separating fish flesh from bones, oil, and other non-edible components. The resulting product is highly protein-rich—containing about 80% protein—and has a much lower ash content than other derivatives such as fish meal. Importantly, FPC can be manufactured from nearly all types of fish, including underutilized species and fishery by-products, making it a sustainable ingredient option.

The Food and Agriculture Organization (FAO) categorizes FPC into three main types based on taste, fat content, and suitability for consumption (Barzana and García-Garibay, 1994):

1. **Type A:** A tasteless, deodorized variety containing less than **0.75% fat**. Due to its neutral sensory characteristics, this type is considered the most suitable for direct human consumption.
2. **Type B:** A moderately flavoured preparation, similar to fish meal, with a fat content not exceeding **3%**.
3. **Type C:** A crude fish meal made under sanitary conditions but with strong flavor and odor, which significantly limits its acceptability even at minimal inclusion levels in food products.

Among these, Type A stands out for its versatility in fortification because of its mild taste and favourable organoleptic qualities. It can be incorporated into a wide range of food products without significantly altering their sensory appeal. Examples of fortified products with FPC include bread, biscuits, noodles, soups, infant foods, and cereal-based products (Table 2).

Thus, FPC not only provides a sustainable way to utilize fish resources and by-products but also serves as an effective protein fortificant to help combat malnutrition, particularly in regions where protein deficiency remains a challenge.

Table 2. FPC-fortified food products

Fortified Food Product	Source (Fish species)	Degree of Fortification (%)	References
Extruded corn snacks	<i>Pollachius virens</i>	18	Shaviklo, <i>et al.</i> , 2014
Popcorn	<i>Pollachius virens</i>	9.0	Shaviklo, <i>et al.</i> , 2015
Extruded snack	<i>Sardinella longiceps</i> & <i>Saurida tumbil</i>	10	Ganesan, Rathnakumar, <i>et al.</i> , 2017
Pasta	<i>Pseudophycis bachus</i>	20	Desai, <i>et al.</i> , 2018
Biscuit	<i>Acipenser sinensis</i>	10	Abraha <i>et al.</i> , 2018
Health drink	<i>Saurida tumbil</i>	10	Rathnakumar <i>et al.</i> , 2018
Pasta	<i>Pseudophycis bachus</i>	20	Desai, 2019
Cookies	<i>Micropogonias undulatus</i>	5.0	Mori <i>et al.</i> , 2020

Fish Protein Hydrolysate (FPH)

Fish Protein Hydrolysate (FPH) is a concentrated source of amino acids, typically produced by breaking down fish proteins through enzymatic or chemical hydrolysis (Unnikrishnan *et al.*, 2021). Unlike Fish Protein Concentrate (FPC), the preparation of FPH does not involve the extensive removal of water or oil (Kumoro *et al.*, 2022). Because of its superior solubility and functional attributes, FPH is often regarded as a more promising ingredient for use in functional foods compared to FPC.

In its liquid state, FPH generally contains about 90% moisture, which makes it unstable for long-term

storage and difficult to transport. To overcome these limitations, it is commonly subjected to dehydration processes, which enhance stability and extend shelf life (Petrova, Tolstorebrov, and Eikevik, 2018).

The quality of FPH is largely influenced by several factors, including the hydrolysis method applied, the processing conditions, the type of fish raw material used, and the choice of enzymes during production (Chalamaiah et al., 2012). However, one of the main drawbacks of FPH is its bitterness. This undesirable taste arises because protein hydrolysis exposes hydrophobic amino acids, which then interact with specific bitter taste receptors on the tongue, creating a distinct bitter flavor (Idowu and Benjakul, 2019).

The bitterness often associated with fish protein hydrolysates is largely attributed to short-chain peptides that contain hydrophobic amino acids such as tryptophan, phenylalanine, isoleucine, tyrosine, valine, and leucine (Fan et al., 2019). Studies show that peptides with molecular weights below 6 kDa and hydrophobicity (Q) values exceeding 1400 cal/mol tend to produce this bitter taste (Benjakul et al., 2014).

The Q value is a measure of the average free energy needed to transfer amino acid side chains from a hydrophobic medium like ethanol to a hydrophilic medium such as water. A higher Q value signifies stronger hydrophobic interactions, which are strongly linked to the perception of bitterness (Ney, 1971).

To improve the sensory quality and acceptability of FPH, it is essential to adopt processing strategies that reduce the generation of these low-molecular-weight, highly hydrophobic peptides. Techniques such as controlled enzymatic hydrolysis, membrane filtration, and enzymatic debittering are commonly used to minimize bitterness and expand the application of FPH in fortified food products.

Table 3. FPH-fortified food products

Source (Fish species)	Fortified Food Product	Degree of Fortification (%)	References
<i>Rastrelliger kanagurta</i>	Milk	0.2	Yarnpakdee, et al., 2012
<i>Micromesistius poutassou</i>	Beverage	4.16	Egerton, et al., 2018
<i>Salmo salar</i>	Cracker	5.0	Idowu et al., 2019
<i>Thunnus albacares</i>	Mayonnaise	15	Unnikrishnan et al., 2020
<i>Salmo salar</i> (frame)	Biscuit	3.5	Singh, et al., 2020
<i>Cynoscion guatucupa</i>	Yoghurt	2.5	Lima et al., 2021
<i>Thunnus albacares</i>	Health beverage	5.0	Unnikrishnan et al., 2021
<i>Micromesistius poutassou</i>	Semolina pasta	–	Khodaei et al., 2023

Fish Oil and Its Role in Food Fortification

Fish oil is mainly obtained from fatty fish such as anchovies, sardines, mackerel, and salmon through a stepwise extraction method. In this process, the fish are first cooked, which causes the proteins to coagulate and release the oil and water stored inside the tissues. This mixture is then pressed to separate the liquid from the solids, resulting in fish oil and a solid protein-rich by-product known as fish meal (Pike and Jackson, 2010).

Nutritionally, fish oil is highly valued because it contains two important omega-3 fatty acids: eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These fatty acids are linked with numerous health benefits, such as improving brain function and reducing the risk of heart disease. At room temperature, fish oil remains liquid, but it solidifies when cooled to 10–15°C, due to its high level of unsaturated fatty acids. The exact composition of fish oil can vary depending on the type of fish from which it is derived (Pike and Jackson, 2010).

One of the major challenges with fish oil is its susceptibility to oxidation. When exposed to oxygen, the fatty acids oxidize quickly, forming harmful compounds like lipid peroxides and other secondary or tertiary oxidation products. These by-products not only reduce the nutritional quality of the oil but also cause off-flavours, unpleasant odours, shorter shelf life, and potential health risks (Ye, Cui, Taneja, Zhu, and Singh, 2009; Daoud *et al.*, 2019).

To address this issue, researchers have developed microencapsulation technology. This method involves enclosing the fish oil (the “core”) inside a protective outer coating (the “wall”) made from proteins, polysaccharides, lipids, or cellulose-based materials. The coating acts as a barrier that shields the oil from oxygen and environmental stress, thereby improving its stability and shelf life. Moreover, it allows the fish oil to be released in a controlled manner inside the body, ensuring maximum absorption and health benefits (Lavanya *et al.*, 2020).

The microencapsulation process generally starts with the preparation of a stable emulsion, where fish oil droplets are dispersed and coated with wall materials. This emulsion is then subjected to drying methods such as spray drying or freeze drying, which remove the moisture and produce microcapsules containing fish oil droplets.

Besides protecting the oil, microencapsulation also helps in masking the strong fishy taste and odour, thereby improving the sensory qualities of fortified foods. As a result, microencapsulated fish oil is widely used in the fortification of various food products, including dairy items, baked goods, snacks, beverages, and health supplements. Consumers benefit by gaining omega-3 fatty acids in their diet without experiencing the unpleasant taste usually associated with fish oil (Lavanya *et al.*, 2020).

Fish Calcium as a Functional Ingredient

Calcium is a vital mineral that plays a key role in maintaining strong bones and overall skeletal health. When the body does not receive enough calcium, it can result in disorders such as nutritional rickets in children and osteomalacia in adults (Palacios *et al.*, 2021).

One sustainable source of dietary calcium is fish bones, which are an abundant by-product of fish processing. They typically account for 10–15% of the total fish biomass, regardless of the type of

processed product, whether it be fillets, surimi, or other fish-based foods. Instead of being discarded, these bones can be transformed into valuable functional food ingredients (Zakaria *et al.*, 2022).

Structurally, fish bones are made up of both organic and inorganic components, each contributing to their strength and nutritional potential. The organic portion mainly consists of collagen fibrils, which provide flexibility and resilience. Cross-linking within collagen fibers further improves the bone's stability and durability. On the other hand, the inorganic fraction is dominated by hydroxyapatite (HA) crystals, a natural calcium phosphate mineral with the chemical formula $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$. These crystals are embedded within the collagen framework, giving the bones their hardness and rigidity.

To prepare fish bone calcium for human use, the bones are typically shredded, cooked at 121°C, and then dried and ground into powder (Sen *et al.*, 2022). Depending on the application, further treatments such as enzymatic hydrolysis or chemical extraction may be applied to improve texture, solubility, or bioavailability.

Recent studies have shown that fish bones, as well as scales and heads, can be efficiently utilized to develop calcium-rich powders suitable for fortifying a variety of food products. Such applications not only improve the nutritional quality of foods but also contribute to the sustainable use of fishery by-products (Zakaria *et al.*, 2022; Sen *et al.*, 2022).

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