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Food Fortification: Role of Fish-based Derivatives

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Abstract

Fish is recognized as a valuable source of both micro and macronutrients. However, its consumption remains inadequate due to various barriers, such as cost, sensory preferences, and availability. Meanwhile, convenience foods have gained popularity due to their utility, affordability, and accessibility. This review explores the integration of various fish-derived products into convenience foods to address inadequate consumption. Given the inherent perishability of fish, converting it into a relatively stable form can help mitigate these problems to some extent. Various fish-derived products, including Fish protein concentrate (FPC) or Fish powder, Fish protein hydrolysate (FPH), Fish oil, and Fish calcium are a few that find potential application in various foods and are examined in this review along with their incorporation levels.

Keywords: Food fortification, fish protein hydrolysate, fish protein concentrate, fish powder, fish oil, fish calcium

Introduction

Food fortification refers to the addition of micronutrients to processed foods. It involves adding nutrients like vitamins and minerals to a food or condiment, called the carrier food or food vehicle, to enhance its nutritional value (Poniedzialek, Perkowska, & Rzymski, 2020). When the existing diet doesn't provide enough essential nutrients for a population, fortifying food with specific micronutrients can make a significant difference in public health outcomes.

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Types of Food Fortification

Food fortification efforts can be broadly categorized into mandatory and voluntary fortification (Fig. 1).

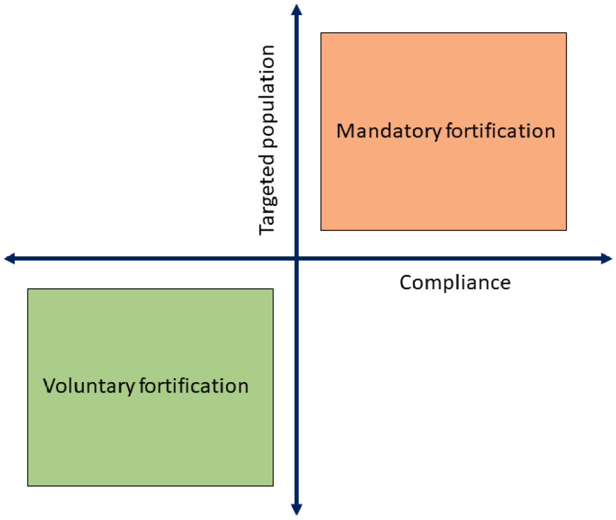

Fig. 1. Mandatory v/s Voluntary fortification

Mandatory and voluntary fortification vary primarily in terms of compliance and the extent of the population they target:

Mandatory Fortification: Government-mandated fortification is designed to reach a wider demography to ensure that essential nutrients are added to commonly consumed foods, thereby addressing nutritional deficiencies and improving public health on a large scale. Examples include Iodized salt, Folic acid in flour, Niacin in bread, Vitamin D in milk, margarine, and breakfast cereals, Fluoride in water supplies etc.

Voluntary Fortification: This occurs when food manufacturers choose to add micronutrients to processed foods, often in response to consumer demand for healthier options. These additions may also serve as strategic marketing tactics for selling products.

The Need for Fortification

Despite the importance of a balanced diet, national surveys indicate inadequate consumption of essential nutrients due to various barriers such as cost, sensory perception, beliefs, availability, and cooking skills (Christenson, O'Kane, Farmery, & McManus, 2017). The latest report from the Food and Agriculture Organization (FAO, 2022) underscores the significance of nutrient-rich foods in combating diet-related diseases compared to calorie-rich alternatives. This is particularly important in low-income communities that often have easier access to unhealthy convenience foods, contributing to non-communicable diseases (NCDs) linked to unhealthy diets high in carbohydrates, fats, and salt (Hawkes, Ruel, Salm, Sinclair, & Branca, 2020). The changing landscape of global dietary habits driven by factors such as urbanization, rising incomes, and busier lifestyles necessitates a shift in fortification strategies. The notable increase in the consumption of convenience foods represents an opportunity to address nutritional gaps in modern diets while meeting the increasing demand for quick and easy meal options.

Fish as a Functional Food Ingredient

In the context of food fortification, fish stands out as an exemplary functional food ingredient. Fish is an economical protein source, especially in developing nations (Béné et al., 2015), and is essential for balanced nutrition. In 2019, aquatic foods contributed to 7.0 % of the global average protein intake (FAO, 2022). Fish is particularly valuable for fortification due to its rich array of beneficial components, including high-quality proteins, omega-3 fatty acids, essential vitamins and minerals, antioxidants etc. The European Food Safety Authority's Panel on Nutrition, Novel Foods, and Food Allergens (NDA) suggests consuming seafood 1-2 times weekly, or 3-4 times weekly during pregnancy, citing benefits such as improved neuron development in children and reduced risk of coronary heart disease mortality in adults (EFSA, 2014). Hicks et al. (2019) estimated that the nutrients in fish catch alone could meet the dietary needs of populations residing within hundred kilometres of coastal areas in countries with prevalent nutrient deficiencies.

Table 1. Beneficial components in fish

Category	Types	Benefits	References
Protein	Sarcoplasmic Myofibrillar Stroma	Contains all essential amino acids necessary for muscle repair, growth, and overall bodily functions.	Chalamaiah, Kumar, Hemalatha, & Jyothirmayi, 2012
Omega-3 Fatty Acids	EPA (Eicosapentaenoic Acid)	Reduces inflammation, lowers heart disease risk, reduces triglycerides, lowers blood pressure, prevents blood clots	Calder, 2017
	DHA (Docosahexaenoic Acid)	Vital for brain health, enhances visual acuity, enhances cognitive function	Yurko-Mauro, et al., 2010
Vitamins and Minerals	Vitamin D	Bone health, immune function, inflammation reduction	Holick, 2007
	Vitamin B_{12}	Nerve function, DNA synthesis, red blood cell formation	Stabler, 2013
	Iodine	Thyroid hormone production, metabolism regulation	Zimmermann, 2009
	Selenium	Antioxidant, supports thyroid function	Rayman, 2012
	Calcium	Bone strength, muscle function	Weaver, 2014
Antioxidants	Astaxanthin	Neutralizes free radicals, reduces chronic disease risk, protects cells, supports overall health and well-being	Guerin, Huntley, & Olaizola, 2003

Fish-based fortification offers unique advantages over general fortification. Fish provides a wide range of essential nutrients in a single source, making it an efficient choice for fortification (Table 1). The diverse nutrient content of fish can help address multiple nutritional deficiencies simultaneously. Many nutrients in fish, particularly omega-3 fatty acids and certain minerals, are highly bioavailable, which means they are easily absorbed and utilized by the body. In this regard, various fish derived products can be considered including FPC, FPH, Fish oil, Fish calcium etc.

Fish protein concentrate (FPC) or Fish powder

Fish protein concentrate (FPC) or fish powder is a stable fish preparation with a higher concentration of protein than its source fish (Kumoro et al., 2022). It is derived in powder form and is produced by separating the meat, free of bones, oil, and other extraneous matter. FPC is rich in protein (approximately 80%) and has a lower ash content compared to other derivatives like fish meal. In general, all types of fish and fishery residue can be used to produce FPC. According to the Food and Agricultural Organization, FPCs can be classified into three types (Barzana & Garía-Garibay, 1994).

1. Type A - tasteless, deodorized, fat content less than 0.75 %.
2. Type B - moderate taste, a fish meal containing not more than 3% fat.
3. Type C – a crude fish meal prepared in sanitary conditions, with strong flavour and odour, low acceptance even for minimum inclusion in foods.

The neutral taste and organoleptic properties of type A make it the best for human consumption. The following lists some of the FPC-fortified food products (Table 2).

Fish protein hydrolysate (FPH)

FPH is usually a rich concentrate of amino acids obtained by digesting fish proteins through enzymatic or chemical treatments (Unnikrishnan et al., 2021). Unlike FPC, FPH does not remove significant amounts of oil and water (Kumoro et al., 2022). FPH has more potential as a functional food ingredient than FPC due to its better solubility and functional characteristics. FPH consists of hydrolyzed proteins containing approximately 90% moisture in their liquid form, making it relatively unstable for long-term storage and challenging to transport. Hence, FPH is dehydrated for better stability and transportation (Petrova, Tolstorebrov, & Eikevik, 2018). FPH quality highly depends on how they are hydrolyzed, the reaction conditions under which they are formed, and the raw materials and enzymes used (Chalamaiah et al., 2012). Bitterness in fish protein hydrolysates (FPH) is primarily caused when the breakdown of larger proteins reveals hydrophobic amino acids. These amino acids, once exposed interact with bitter specific taste receptors, leading to a bitter sensation (Idowu & Benjakul, 2019).

Table 2. FPC-fortified food products

Source	Fortified food product	Degree of fortification (%)	References
Pollachius virens	Extruded corn snacks	18	Shaviklo, Dehkordi, & Zangeneh, 2014
Pollachius virens	Popcorn	9.0	Shaviklo, Dehkordi, & Zangeneh, 2015
Sardinella longiceps & *Saurida tumbil*	Extruded snack	10	Ganesan, Rathnakumar, Nicy, & Vijayarahavan, 2017
Pseudophycis bachus	Pasta	20	Desai, Brennan, & Brennan, 2018
Acipeneser sinensis	Biscuit	10	Abraha et al., 2018
Saurida tumbil	Health drink	10	Rathnakumar & Pancharaja, 2018
Pseudophycis bachus	Pasta	20	Desai, 2019
Micropogonias undulatus	Cookies	-	Mori et al., 2020
Ctenopharyngodon Idella	Baked snacks	5.0	Nawaz, Huma, Nadeem, & Yasin, 2021
Coilia dussumieri & *Sardinella fimbriata*	Ready-to-use food product	-	Mamun, Rahman, Rahman, & Islam, 2022

Table 3. FPH-fortified food products

Source	Fortified food product	Degree of fortification (%)	References
Rastrelliger kanagurta	Milk	0.2	Yarnpakdee, Benjakul, Kristinsson, & Maqsood, 2012
Micromesistius potassium	Beverage	-	Egerton, Culloty, Whooley, Stanton, & Ross, 2018
Salmo salar	Cracker	4.16	Idowu et al., 2019
Thunnus albacares	Mayonnaise	5.0	Unnikrishnan et al., 2020
Salmo salar frame	Biscuit	15	Singh, Benjakul, & Huda, 2020
Cynoscion guatucupa	Yoghurt	3.5	Lima et al., 2021
Thunnus albacares	Health beverage	2.5	Unnikrishnan et al., 2021
Micromesistius poutassou	Semolina pasta	5.0	Khodaei, Forde, Noci, & Ryan, 2023

Peptides with lower molecular weights, especially those containing hydrophobic amino acids such as tryptophan, phenylalanine, isoleucine, tyrosine, valine, and leucine, are more likely to contribute to this bitterness (Fan et al., 2019). Peptides with hydrophobicity (Q) values greater than 1400 cal per mole and molecular masses below 6 kDa are reported to exhibit bitterness (Benjakul et al., 2014). The Q value represents the average free energy required to transfer the side chains of amino acids from ethanol (a relatively hydrophobic environment) to water (a more hydrophilic environment), with higher Q values indicating stronger hydrophobic interactions (Ney, 1971). Processing methods that limit the formation of smaller peptides can help reduce bitterness thereby improving the sensory properties and its applicability. The following table lists some fish protein hydrolysate (FPH) fortified food products (Table 3).

Fish oil

Fish oil is extracted mainly from fatty fish such as anchovies, sardines, mackerel, salmon, etc. through a multi-step process. During this process, the fish are cooked, which causes the proteins to coagulate and release the oil and water that are trapped within. This is followed by pressing, which separates the oil from the solids, yielding fish oil and a protein-rich solid by-product (fish meal). Fish oil is rich in two potent omega-3 fatty acids: eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). At room temperature, fish oils are liquid but solidify below 10-15°C, on being rich in unsaturated fatty acids. Their composition varies based on the kind of fish they are derived from (Pike & Jackson, 2010). The fatty acids in the oil undergo rapid oxidation on exposure to oxygen and generate undesired lipid peroxides, secondary and tertiary oxidation products that pose health risks, reduce shelf-life stability, and limit the use of fish oil as a food additive (Ye, Cui, Taneja, Zhu, & Singh, 2009; Daoud et al., 2019). Microencapsulation is a process used to create small particles that contain an active substance (the core) surrounded by a protective outer layer (the wall). This wall acts as a physical barrier, isolating the core from the external environment. With micro encapsulation technique, the core (fish oil) is entrapped within a wall material (proteins, lipids, polysaccharide gums, and cellulose) to protect the core from oxidative stress. It also allows the core to be released to target areas in the body in a controlled manner (Lavanya, Kathiravan, Moses, & Anandharamakrishnan, 2020). The microencapsulation process starts by emulsifying fish oil to form a stable emulsion. This emulsion is then mixed with a solution of dissolved wall materials that act as protective coatings for the oil droplets. The mixture is subsequently dehydrated using methods like spray drying or freeze drying to eliminate moisture, resulting in microcapsules that contain fish oil droplets encased in a protective wall material (Fig. 2).

Microencapsulated fish oil (fish oil emulsion) not only enhances stability but also masks undesirable tastes or odours, resulting in higher sensory acceptance compared to regular fish oil. The following table lists some fish oil-fortified food products (Table 4).

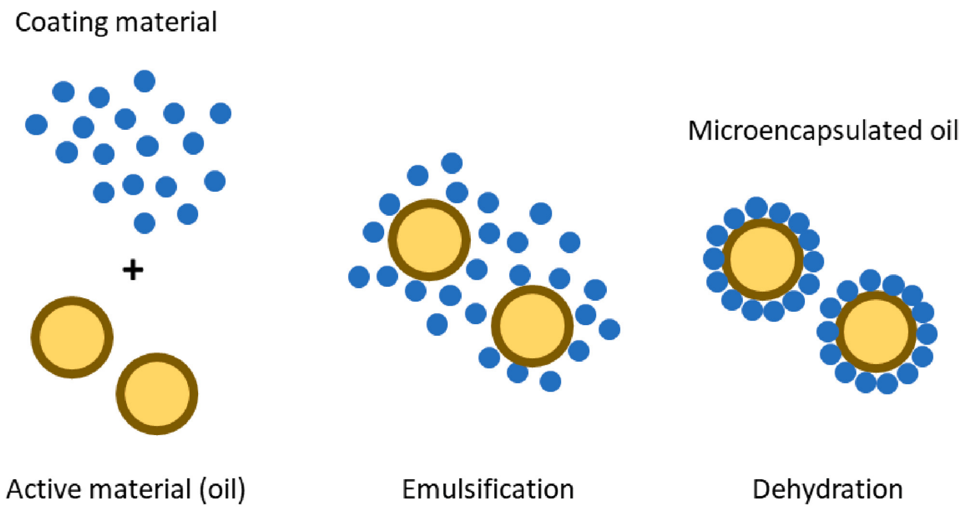

Fig. 2. Basic mechanism of microencapsulation process

Fish calcium

Calcium is an essential mineral primarily found in the skeleton, providing structural support for the body. Insufficient calcium consumption can lead to nutritional rickets in children and osteomalacia in adults (Palacios et al., 2021). Fish calcium is primarily sourced from bones. Fish bones are a significant by-product of fish processing, comprising about 10-15% of the total fish biomass. This percentage is consistent across various processed fish products, such as fillets and surimi. The composition of fish bones includes both organic and inorganic components, each with important applications and nutritional benefits. The organic matrix is primarily composed of collagen fibrils, a protein that provides structural support and flexibility to bones, with cross-linking enhancing their strength and stability. The inorganic part mainly consists of hydroxyapatite (HA) crystals, a naturally occurring form of calcium phosphate with the chemical formula $Ca_{10}(PO_4).6(OH)$. These HA crystals are embedded within the collagen matrix, imparting hardness and rigidity to the bones (Zakaria, Yatim, Ali, & Rastegari, 2022). A typical preparation method for extracting calcium involves shredding and cooking fish bones at 121°C to remove excess liquid, followed by drying and grounding to a powder form (Sen, Naveena, Banerjee, & Muthukumar, 2022). Additional treatments like enzymatic or chemical processes may be needed depending on the intended purpose or desired characteristics. The utilization of calcium in fish bone, scale, and head as a functional food ingredient has been studied extensively in recent years. Table 5 presents examples of food products fortified with fish calcium.

Nutritional aspects of fish fortified foods

Fortifying food products with fish-derived ingredients such as FPC, FPH, fish oil, fish calcium etc. can significantly enhance their nutritional profile. Studies consistently show that all fish-fortified food products exhibited higher protein content compared to unfortified or control groups (Shaviklo et al., 2014; Shaviklo et al., 2015; Mori et al., 2020; Nawaz et al., 2021). FPH, rich in small peptides and amino acids, provides a highly bioavailable source of essential nutrients, boosting protein levels in products like crackers and biscuits while reducing fat, carbohydrate, and energy values, aligning with dietary preferences for lower calorie intake and healthier options (Idowu et al., 2019; Singh et al., 2020). Similarly, incorporating fish oil into foods like cheese, yoghurt, chicken nuggets, and ice cream significantly increased their omega-3 fatty acid content, specifically EPA and DHA, which are essential for human health but cannot be synthesized by the body (Ye et al., 2009; Estrada et al., 2011; Hejazian et al., 2016; Lee et al., 2016; Andajani, 2016; Ghorbanzade et al., 2017; Turkmen et al., 2019; Raeisi et al., 2021). Fortifying foods with fish bone powder enhance their calcium and phosphorus levels, increase protein content, and reduce fat, carbohydrate, and energy values. Studies have also indicated that the bioavailability of calcium and phosphorus can be further improved by reducing the particle size of the fishbone (Yin et al., 2016; Benjakul & Karnjanapratum, 2018; Hemung et al., 2018; Fong-In et al., 2020; Asikin et al., 2024). Overall, the use of fish derived bioactives in food boosted essential nutrient contents, thereby meeting consumer demand for healthier, low-calorie food options.

Challenges of fish-based fortification

Sensory Acceptability

Sensory acceptability holds a pivotal role in determining the feasibility of fortification, particularly when dealing with ingredients such as FPC, FPH, and fish oil known for their distinctive 'fishy' smell. Masking this flavour remains a significant challenge in fortification efforts (Andajani, 2016). Studies have shown that incorporating higher levels of fish powder in food products can negatively impact density, hardness, expansion, and mouthfeel (Turkmen et al., 2019; Sridhar et al., 2021). Furthermore, increasing levels of fish powder in products like pasta have resulted in increased cooking loss and decreased cooking time, but have positively impacted pasta's extensibility and, thereby, its sensory attributes (Desai, 2019). Bitterness in FPH poses a challenge to its incorporation into diets at higher levels (Idowu et al., 2019). When fortifying dairy products with fish oil, maintaining sensory acceptability is crucial for consumer satisfaction, with research highlighting the importance of minimizing fishy off-flavours and enhancing overall sensory characteristics (Andajani, 2016; Moghadam et al., 2019). Incorporating microencapsulated fish oil can help mitigate these undesirable sensory attributes (Sridhar et al., 2021). Studies on fortifying whole wheat crackers with tuna bone bio-calcium powder (<30 %) have indicated no adverse effects on texture, colour, and sensory properties (Benjakul

Table 4. Fish oil-fortified food products

Fortified Food Product	Degree of Fortification	Form	References
Cheese	3 - 4 %	Emulsion	Ye et al., 2009
Yoghurt	2.0 % wt/vol	Microencapsulate	Estrada, Boeneke, Bechtel, & Sathivel, 2011
Ice cream	-	Encapsulate	Andajani, 2016
Yoghurt	-	Encapsulate	Liu et al., 2016
Cheese	1.0 - 5.0%	Encapsulate	Hejazian, Takami, & Shendi, 2016
Yoghurt	15ml/10g	Nano-encapsulate	Ghorbanzade, Jafari, Akhavan, & Hadavi, 2017
Probiotic fermented milk	6.0%	Nano-encapsulate	Moghadam, Pourahmad, Mortazavi, Davoodi, & Azizinezhad, 2019
Yoghurt	0.3% and 0.5%	Deodorized fish oil	Turkmen, Senel, & Ceren, 2019
Yoghurt	2.5% FPH and 1% FO	Double emulsion (W1/O/W2)	Jamshidi, Shabanpour, Pourashouri, & Raeisi, 2019
Mayonnaise	13 wt%	Microcapsules (spray-dried)	Rahmani-Manglano et al., 2020
Nuggets	4.0%	Encapsulate	Raeisi, Ojagh, Pourashouri, Salaün, & Quek, 2021
Sago-analog rice	5.0%	Pure	Syahrul, Dewita, & Sidauruk, 2021
Bread	5.0%	Microencapsulate	Sridhar, Sharma, Choudhary, Dikkala, & Narsaiah, 2021
Oat-based Beverages	-	Emulsions	Fernandez et al., 2021
Nutrition Drink	30%	Microencapsulation	Khoonin, Shantavasinkul, Santivarangkna, & Trachootham, 2022
Dairy Products	-	Emulsions	Savatinova, & Ivanova, 2024
Mayonnaise	3%	Microcapsules (spray-dried)	Rahim et al., 2024

& Karnjanapratum, 2018). However, coarse particles of fish bone (>100 ìm) negatively affected sensory quality, which can be minimized by decreasing particle size (Yin et al., 2022). Hence various studies undertaken on the fortification of food products with fish-derived components have indicated both positive as well as negative influence on the sensorial attributes and hence needs to be optimized according to the intended product.

Storage Stability

The key determinant influencing the shelf life and stability of fish-fortified products is primarily the fat content. Maintaining oxidative stability is crucial for ensuring the quality and longevity of food products fortified with fish oil. Moghadam et al. (2019) used Gum Arabic as the wall material for fish oil nanoencapsulation and reported that nano-encapsulated fish oil did not adversely affect overall sensory acceptance. Ghorbanzade et al. (2017) reported that nano-liposome encapsulation effectively reduced acidity, syneresis, and peroxide value in yoghurt even after 21 days of storage compared to direct incorporation of fish oil. Microencapsulation can be a valuable strategy to mitigate the rapid oxidation of fatty acids during fortification with fish oil by minimizing exposure to atmospheric oxygen. Lima et al. (2021) investigated yoghurts fortified with both free and microencapsulated stripped weakfish protein hydrolysates, revealing enhanced stability through microencapsulation. This improvement in stability was attributed to microencapsulation, which enhanced the hydrolysate's stability within the

Table 5. Fish calcium fortified food products

Source	Fortified food product	Degree of fortification (%)	Form	References
Skipjack Tuna	Cracker	30	Bone bio-calcium powder	Benjakul & Karnjanapratum, 2018
Tilapia	Baton Sale	7.0	Bone powder	El-Zainy,El-Kewawy, & El ESawey, 2018
Silver carp	Fish emulsion sausage	0.5-1.0	Bone powder	Hemung, Yongsawatdigul, Chin, Limphirat, & Siritapetawee, 2018
Grass carp	Fried snacks	10-20	Bone paste	Nawaz et al., 2019
Salmon	Cracker	12.5	Bio calcium	Idowu et al., 2019
Milkfish	Rengginang	1.0	Bone powder	Eris, Munandar, Kartina, Meutia, & Anggraeni, 2020
Tilapia	Cookies	20	Bone powder	Fong-In, Phosri, Suttiprapa, Pimpangan, & Utama-Ang, 2020
Tilapia	Cookies	2.0	Bone powder	Njoroge & Lokuruka, 2020
Pangas catfish, Spanish mackerels & Snakehead	Choco chips cookies	10	Bone powder	Ananda & Anggraeni, 2021
Tuna	Porridge	1.0	Bone meal	Tangke, Daeng & Katiandagho, 2021
Fishbone	Tortilla	0.2	Bone hydroxyapatite	Liaqat, Ahmed, Ali, Akbar, & Khalid, 2022
Tuna	Stick	25	Bone Flour	Sihmawati, 2022
Lutjanus *sp.*	Saddah Gohoge grits	10-20	Bone nano minerals	Husain, Djailani, & Harmain, 2023
Sea bass	Financier	3.0	Fish bone flour	Boronat et al., 2023
Knife -fish	Butter cookies	6.0	Bone powder	Asikin, Kusumaningrum, & Hidayat, 2024

yoghurt matrix, leading to improved water retention and reduced whey separation during storage. Additionally, Singh et al. (2020) demonstrated that biscuits fortified with debittered salmon frame hydrolysate exhibited an extended shelf life without compromising overall physicochemical and textural properties.

Future Prospects

Looking forward, the future of fish-based fortification rests on several critical areas that necessitate advancement and innovation. Primarily, enhancing sensory masking techniques is imperative to effectively mitigate the distinct fishy odours and flavours associated with products like fish protein concentrate, fish hydrolysate, and fish oil, thereby bolstering overall consumer acceptability. Concurrently, developing robust stability solutions and formulations for fortified products, especially those containing oxidation-prone components such as fish oils, is essential to uphold product quality and extend shelf life. Expanding the application of fish-based fortification beyond traditional foods such as yoghurt or crackers to encompass a wider range of products holds promise for diversifying nutritional offerings and catering to diverse dietary preferences. Comprehensive consumer acceptance studies across various demographics and cultural contexts are crucial to broadly understand and address consumer perceptions and preferences towards fortified products. Furthermore, continued assessment of the nutritional impact and health benefits of fish-based fortification, including studies on bioavailability, nutrient retention after processing, and long-term dietary implications, will provide essential insights into the efficacy and potential health implications of these fortified foods. By advancing in these interconnected areas, the field of fish-based fortification can significantly enhance both nutritional efficacy and consumer acceptance globally, ensuring these products meet the evolving needs of diverse markets.

Conclusion

The integration of fish-derived bioactive ingredients into food products offers substantial nutritional advantages, that can meet the ensuring demand of the customers. Despite challenges like sensory acceptability, storage stability, etc. optimization of protocols for process and product development as well as adoption of innovative techniques is promising in overcoming the hurdles, ensuring that fortified foods maintain the desired quality and be appealing to all category of customers.

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References

Abraha, B., Mahmud, A., Admassu, H., Yang, F., Tsighe, N., Girmatsion, M., Xia, W., Magoha, P., Yu, P., Jiang, Q., & Xu, Y. (2018). Production and quality evaluation of biscuit incorporated with fish fillet protein concentrate. *Journal of Nutrition & Food Sciences, 8*(6), 1000744. https://doi.org/10.4172/2155-9600.1000744.

Ananda, S., & Anggraeni, A. A. (2021). Substitution of fishbone powder in the development of choco chips cookies. *IOP Conference Series: Earth and Environmental Science, 672*(1), 012062. https://doi.org/10.1088/1755-1315/672/1/012062.

Andajani, P. T. (2016). Microencapsulated mixture of fish oil and fortified in ice cream. *Jurnal Ilmu dan Teknologi Hasil Ternak* (*JITEK*), *11*(2), 1-10. https://doi.org/10.21776/ub.jitek.2016.011.02.1.

Asikin, A. N., Kusumaningrum, I., & Hidayat, T. (2024). Chemical characteristics of butter cookies with knifefish (*Chitalla* sp.) bone flour addition as a healthy snack of high calcium. *Food Research, 8*(2), 78-83. https://doi.org/10.26656/fr.2017.8(2).046.

Barzana, E., & Garía-Garibay, M. (1994). Production of fish protein concentrates. In A. M. Martin (Eds.), *Fisheries Processing: biotechnological applications* (pp. 206-222). Springer, Boston, MA.

Béné, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G. I., & Williams, M. (2015). Feeding 9 billion by 2050–Putting fish back on the menu. *Food Security*, *7*, 261-274. https://doi.org/10.1007/s12571-015-0427-z.

Benjakul, S., & Karnjanapratum, S. (2018). Characteristics and nutritional value of whole wheat cracker fortified with tuna bone bio-calcium powder. *Food Chemistry*, *259*, 181-187. https://doi.org/10.1016/j.foodchem.2018.03.124.

Benjakul, S., Yarnpakdee, S., Senphan, T., Halldorsdottir, S. M., & Kristinsson, H. G. (2014). Fish protein hydrolysates: production, bioactivities, and applications. In H. G. Kristinsson (Eds.), *Antioxidants and functional components in aquatic foods* (pp. 237-281). John Wiley & Sons, Ltd., New Jersey.

Boronat, Ò., Sintes, P., Celis, F., Díez, M., Ortiz, J., Aguiló-Aguayo, I., & Martín-Gómez, H. (2023). Development of added-value culinary ingredients from fish waste: Fish bones and fish scales. *International Journal of Gastronomy and Food Science*, *31*, 100657. https://doi.org/10.1016/j.ijgfs.2022.100657.

Calder, P. C. (2017). Omega-3 fatty acids and inflammatory processes: from molecules to man. *Biochemical Society Transactions*, *45*(5), 1105-1115. https://doi.org/10.1042/BST20160474.

Chalamaiah, M., Kumar, B. D., Hemalatha, R., & Jyothirmayi, T. (2012). Fish protein hydrolysates: proximate composition, amino acid composition, antioxidant activities and applications: a review. *Food Chemistry*, *135*(4), 3020-3038. https://doi.org/10.1016/j.foodchem.2012.06.100.

Christenson, J. K., O'Kane, G. M., Farmery, A. K., & McManus, A. (2017). The barriers and drivers of seafood consumption in Australia: A narrative literature review. *International Journal of Consumer Studies*, *41*(3), 299-311. https://doi.org/10.1111/ijcs.12342.

Daoud, S., Bou-Maroun, E., Dujourdy, L., Waschatko, G., Billecke, N., & Cayot, P. (2019). Fast and direct analysis of oxidation levels of oil-in-water emulsions using ATR-FTIR. *Food chemistry*, *293*, 307-314. https://doi.org/10.1016/j.foodchem.2019.05.005.

Desai, A. S. (2019). The effect of fish protein powder on the physiochemical, nutritional, and sensory properties of cereal-based products: A thesis submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy at Lincoln University (Doctoral dissertation, Lincoln University).

Desai, A., Brennan, M. A., & Brennan, C. S. (2018). The effect of semolina replacement with protein powder from fish (*Pseudophycis bachus*) on the physicochemical characteristics of pasta. *LWT*, *89*, 52-57. https://doi.org/10.1016/j.lwt.2017.10.023.

EFSA Dietetic Products, Nutrition, and Allergies (NDA). (2014). Scientific Opinion on health benefits of seafood (fish and shellfish) consumption in relation to health risks associated with exposure to methylmercury. *EFSA Journal*, *12*(7), 3761. https://doi.org/10.2903/j.efsa.2014.3761.

Egerton, S., Culloty, S., Whooley, J., Stanton, C., & Ross, R. P. (2018). Characterization of protein hydrolysates from blue whiting (*Micromesistius poutassou*) and their application in beverage fortification. *Food Chemistry*, *245*, 698-706. https://doi.org/10.1016/j.foodchem.2017.10.107.

El-Zainy, A. R. M., El-Kewawy, H. A. M., & El-ESawey, A. H. (2018). Utilization of fish bone and egg shell to nutritional support of baton sale. *Bulletin of the National Nutrition Institute of the Arab Republic of Egypt*, *52*(1), 1-21. https://dx.doi.org/10.21608/bnni.2018.31437.

Fernandez, B. E. E., Klassen, P., Mazurak, V., Chen, L., Prado, C. M., & Wismer, W. V. (2021). Acceptance of oat based beverages tailored for patients with cancer. *Journal of Food Science*, *86*(6), 2671-2683. https://doi.org/10.1111/1750-3841.15776.

Eris, F. R., Munandar, A., Kartina, A. M., Meutia, & Anggraeni, D. (2020). Utilization of Milkfish (*Chanos chanos*) bone powder in making of rengginang, local food of baduy tribe. *Food ScienTech Journal*, *2*(1), 44-54. https://doi.org/10.33512fsj.v2i1.8810.

Estrada, J. D., Boeneke, C., Bechtel, P., & Sathivel, S. (2011). Developing a strawberry yoghurt fortified with marine fish oil. *Journal of Dairy Science*, *94*(12), 5760-5769. https://doi.org/10.3168/jds.2011-4226.

Fan, W., Tan, X., Xu, X., Li, G., Wang, Z., & Du, M. (2019). Relationship between enzyme, peptides, amino acids, ion composition, and bitterness of the hydrolysates of Alaska pollock frame. *Journal of Food Biochemistry*, *43*(4), e12801. https://doi.org/10.1111/jfbc.12801.

FAO. (2022). *The State of World Fisheries and Aquaculture 2022 - Towards Blue Transformation*. FAO, Rome.

Fong-In, S., Phosri, P., Suttiprapa, S., Pimpangan, T., & Utama-Ang, N. (2020). Effect of substitution of wheat flour with Nile tilapia bone powder on the quality characteristics of cashew nut cookies. *Chiang Mai University Journal of Natural Sciences*, *19*(4), 997-1011. https://doi.org/10.12982/CMUJNS.2020.0065.

Ganesan, P., Rathnakumar, K., Nicy, B. A., & Vijayarahavan, V. (2017). Improvement of nutritional value of extruded snack product by incorporation of blanched dried fish powder from sardine and Lizard fish and selection by organoleptic evaluation. *Journal of Entomology and Zoology Studies*, *5*(6), 2552-2554.

Ghorbanzade, T., Jafari, S. M., Akhavan, S., & Hadavi, R. (2017). Nano-encapsulation of fish oil in nano-liposomes and its application in fortification of yoghurt. *Food Chemistry*, *216*, 146-152. https://doi.org/10.1016/j.foodchem.2016.08.022.

Guerin, M., Huntley, M. E., & Olaizola, M. (2003). Haematococcus astaxanthin: applications for human health and nutrition. *Trends in Biotechnology*, *21*(5), 210-216. https://doi.org/10.1016/S0167-7799(03)00078-7.

Hawkes, C., Ruel, M. T., Salm, L., Sinclair, B., & Branca, F. (2020). Double-duty actions: seizing programme and policy opportunities to address malnutrition in all its forms. *The Lancet*, *395*(10218), 142-155. https://doi.org/10.1016/S0140-6736(19)32506-1.

Hejazian, S., Takami, S. H., & Shendi, E. G. (2016). Sensorial properties, chemical characteristics and fatty acids profile of cheese fortified by encapsulated kilka fish oil. *Modern Applied Science*, *10*(3), 208-213. http://dx.doi.org/10.5539/mas.v10n3p208.

Hemung, B. O., Yongsawatdigul, J., Chin, K. B., Limphirat, W., & Siritapetawee, J. (2018). Silver carp bone powder as natural calcium for fish sausage. *Journal of Aquatic Food Product Technology*, *27*(3), 305-315. https://doi.org/10.1080/10498850.2018.1432733.

Hicks, C. C., Cohen, P. J., Graham, N. A. J., Nash, K. L., Allison, E. H., D'Lima, C., Mills, D. J., Roscher, M., Thilsted, S. H., Thorne-Lyman, & MacNeil, M. A. (2019). Harnessing global fisheries to tackle micronutrient deficiencies. *Nature*, *574*(7776), 95-98. https://doi.org/10.1038/s41586-019-1592-6.

Holick, M. F. (2007). Vitamin D deficiency. *The New England Journal of Medicine*, *357*(3), 266-281. https://doi.org/10.1056/NEJMra070553.

Husain, R., Djailani, F., & Harmain, R. M. (2023). Nanomineral fortification on traditional Saddah Gohoge grits. *Food Science and Technology*, *43*. https://doi.org/10.5327/fst.099122.

Idowu, A. T., & Benjakul, S. (2019). Bitterness of fish protein hydrolysate and its debittering prospects. *Journal of Food Biochemistry*, *43*(9), e12978. https://doi.org/10.1111/jfbc.12978.

Idowu, A. T., Benjakul, S., Sinthusamran, S., Pongsetkul, J., Sae-Leaw, T., & Sookchoo, P. (2019). Whole wheat cracker fortified with biocalcium and protein hydrolysate powders from salmon frame: characteristics and nutritional value. *Food Quality and Safety*, *3*(3), 191-199. https://doi.org/10.1093/fqsafe/fyz012.

Jamshidi, A., Shabanpour, B., Pourashouri, P., & Raeisi, M. (2019). Optimization of encapsulation of fish protein hydrolysate and fish oil in $W_1/O/W_2$ double emulsion: Evaluation of sensory quality of fortified yoghurt. *Journal of Food Processing and preservation*, *43*(9), e14063. https://doi.org/10.1111/jfpp.14063.

Khodaei, D., Forde, A., Noci, F., & Ryan, L. (2023). Physicochemical and sensory characteristics of pasta enriched with blue whiting (*Micromesistius poutassou*) fish protein hydrolysate. *International Journal of Food Science & Technology*, *58*(5), 2782-2789. https://doi.org/10.1111/ijfs.16278.

Khoonin, W., Shantavasinkul, P. C., Santivarangkna, C., & Trachootham, D. (2022). Loss of Eicosapentaenoic acid (EPA) after retort sterilization of the EPA-BCAA fortified complete nutrition drink. *Foods*, *11*(14). https://doi.org/10.3390/foods11142023.

Kumoro, A. C., Wardhani, D. H., Kusworo, T. D., Djaeni, M., Ping, T. C., & Azis, Y. M. R. F. (2022). Fish protein concentrate for human consumption: A review of its preparation by solvent extraction methods and potential for food applications. *Annals of Agricultural Sciences*, *67*(1), 42-59. https://doi.org/10.1016/j.aoas.2022.04.003.

Lavanya, M. N., Kathiravan, T., Moses, J. A., & Anandharamakrishnan, C. (2020). Influence of spray-drying conditions on microencapsulation of fish oil and chia oil. *Drying Technology*, *38*(3), 279-292. https://doi.org/10.1080/07373937.2018.1553181.

Liaqat, S., Ahmed, Z., Ali, Q., Akbar, A., & Khalid, N. (2022). Development, characterization, and principal component analysis of fish bone based fortified refined wheat flour tortilla and its organoleptic attributes. *Journal of Food Processing and Preservation*, *46*(11), e17051. https://doi.org/10.1111/jfpp.17051.

Lima, K. O., da Rocha, M., Alemán, A., López-Caballero, M. E., Tovar, C. A., Gómez-Guillén, M. C., Montero, P., & Prentice, C. (2021). Yoghurt fortification by the addition of microencapsulated stripped weakfish (*cynoscion guatucupa*) protein hydrolysate. *Antioxidants*, *10*(10), 1567. https://doi.org/10.3390/antiox10101567.

Liu DiRu, L. D., Zhang TieHua, Z. T., Jiang Nan, J. N., Xi ChunYu, X. C., Sun ChunYan, S. C., Zheng Jian, Z. J., & Guo MingRuo, G. M. (2016). Effects of encapsulated fish oil by polymerized whey protein on the textural and sensory characteristics of low-fat yoghurt. *Polish Journal of Food and Nutrition Sciences*, *66*(3), 189-198. https://doi.org/10.1515/pjfns-2015-0043.

Mamun, A. A., Rahman, M. S., Rahman, M. S., & Islam, M. N. (2022). Studies on utilization of fish powder in the production of ready-to-eat (RTE) extruded snacks. *Journal of Fisheries*, *10*(1), 95-101.

Moghadam, F. V., Pourahmad, R., Mortazavi, A., Davoodi, D., & Azizinezhad, R. (2019). Use of fish oil nanoencapsulated with gum arabic carrier in low fat probiotic fermented milk. *Food Science of Animal Resources*, *39*(2), 309-323. https://doi.org/10.5851%2Fkosfa.2019.e25.

Mori, T., Takahashi, H., Nakano, D., Matsuo, S., Uekusa, Y., & Ito, H. (2020). Quality characteristics and shelf-life of restructured pork ham with added squid powder during refrigerated storage. *Meat science*, *161*, 108019.

Nawaz, A., Huma, N., Nadeem, M. T., & Yasin, M. (2021). Comparative study on nutritional, textural, and sensory quality of meat emulsion-based products supplemented with fish protein hydrolysate and commercial plant protein isolates. *Journal of Food Processing and Preservation*, 45(7), e15854.

Nawaz, A., Xiong, Z., Xiong, H., Chen, L., Wang, P. K., Ahmad, I., Irshad, S., & Ali, S. W. (2019). The effects of fish meat and fish bone addition on nutritional value, texture and microstructure of optimised fried snacks. *International Journal of Food Science & Technology*, *54*(4), 1045-1053. http://dx.doi.org/10.1111/ijfs.13974.

Ney, K. H. (1971). Prediction of bitterness of peptides from their amino acid composition. *Zeitschrift für Lebensmittel-Untersuchung und-Forschung, 147*, 64-68.

Njoroge, J. G., & Lokuruka, M. N. (2020). Sensory acceptability of cookies fortified with tilapia fish bone powder. *Journal of Food Nutrition Research, 2*(2), 94-101. https://doi.org/10.37512/800.

Palacios, C., Hofmeyr, G. J., Cormick, G., Garcia Casal, M. N., Peña Rosas, J. P., & Betrán, A. P. (2021). Current calcium fortification experiences: a review. *Annals of the New York Academy of Sciences*, *1484*(1), 55-73. https://doi.org/10.1111/nyas.14481.

Petrova, I., Tolstorebrov, I., & Eikevik, T. M. (2018). Production of fish protein hydrolysates step by step: technological aspects, equipment used, major energy costs and methods of their minimizing. *International Aquatic Research*, *10*(3), 223-241. https://doi.org/10.1007/s40071-018-0207-4.

Pike, I. H., & Jackson, A. (2010). Fish oil: production and use now and in the future. *Lipid Technology*, *22*(3), 59-61. https://doi.org/10.1002/lite.201000003.

Poniedzialek, B., Perkowska, K., & Rzymski, P. (2020). Food Fortification: What's in It for the Malnourished World? In N. Benkeblia (Eds.), *Vitamins and Minerals Biofortification of Edible Plants*, (pp. 27-44). John Wiley & Sons Ltd., New Jersey.

Raeisi, S., Ojagh, S. M., Pourashouri, P., Salaün, F., & Quek, S. Y. (2021). Shelf-life and quality of chicken nuggets fortified with encapsulated fish oil and garlic essential oil during refrigerated storage. *Journal of Food Science and Technology*, *58*(1), 121-128. https://doi.org/10.1007/s13197-020-04521-3.

Rahim, M. A., Imran, M., Khan, F. A., Al-Asmari, F., Mosa, O. F., Almalki, R. S., & Zongo, E. (2024). Omega-3-Enriched and Oxidative Stable Mayonnaise Formulated with Spray-Dried Microcapsules of Chia and Fish Oil Blends. *ACS omega*, *9*(7), 8221-8228. https://doi.org/10.1021/acsomega.3c08807.

Rahmani-Manglano, N. E., González-Sánchez, I., García-Moreno, P. J., Espejo-Carpio, F. J., Jacobsen, C., & Guadix, E. M. (2020). Development of fish oil-loaded microcapsules containing whey protein hydrolysate as film-forming material for fortification of low-fat mayonnaise. *Foods*, *9*(5), 545. https://doi.org/10.3390/foods9050545.

Rathnakumar, K., & Pancharaja, N. (2018). Development of health mix from lizard fish and its nutritional characteristics. *International Journal of Current Microbiology and Applied Sciences*, *7*(3), 3136-3144. https://doi.org/10.20546/ijcmas.2018.703.362.

Rayman, M. P. (2012). Selenium and human health. *The Lancet*, *379*(9822), 1256-1268. https://doi.org/10.1016/S0140-6736(11)61452-9.

Savatinova, M., & Ivanova, M. (2024). Functional dairy products enriched with omega-3 fatty acids. *Food Science and Applied Biotechnology*, *7*(1), 1-13. https://doi.org/10.30721/fsab2024.v7.i1.301.

Sen, A. R., Naveena, B. M., Banerjee, R., & Muthukumar, M. (2022). Value addition in meat and fish products for human health and nutrition. In A. Kumar, P. Kumar, S. S. Singh, B. H. Trisasongko, M. Rani (Eds.), *Agriculture, Livestock Production and Aquaculture: Advances for Smallholder Farming Systems* (pp. 287-303). Springer, Cham.

Shaviklo, A. R., Dehkordi, A. K., & Zangeneh, P. (2014). Interactions and effects of the seasoning mixture containing fish protein powder/omega 3 fish oil on children's liking and stability of extruded corn snacks using a mixture design approach. *Journal of Food Processing and Preservation*, *38*(3), 1097-1105. https://doi.org/10.1111/jfpp.12068.

Shaviklo, A. R., Dehkordi, A. K., & Zangeneh, P. (2015). Ingredient optimization and children's liking of popcorn seasoned with fish protein powder/Omega-3 Fish Oil. *Journal of International Food & Agribusiness Marketing*, *27*(2), 79-90. https://doi.org/10.1080/08974438.2014.897664.

Sihmawati, R. R. (2022). Performance of Food Quality and Sensory Properties of Stick with Fortification of Fish Bone Flour Tuna and Kale Leaf Extract as Natural Food Coloran. *Food Science and Technology Journal* (*FOODSCITECH*), *5*(1), 31-41. https://doi.org/10.25139/fst.v5i1.4548.

Singh, A., Benjakul, S., & Huda, N. (2020). Characteristics and nutritional value of biscuits fortified with debittered salmon (*Salmo salar*) frame hydrolysate. *International Journal of Food Science & Technology*, *55*(12), 3553-3562. https://doi.org/10.1111/ijfs.14688.

Sridhar, K., Sharma, M., Choudhary, A., Dikkala, P. K., & Narsaiah, K. (2021). Fish and garlic oils hybridized microcapsules: Fortification in functional bread. *Journal of Food Processing and Preservation*, *45*(4), e15346. https://doi.org/10.1111/jfpp.15346.

Stabler, S. P. (2013). Vitamin B12 deficiency. *New England Journal of Medicine*, *368*(2), 149-160. https://doi.org/10.1056/NEJMcp1113996.

Syahrul, S., Dewita, D., & Sidauruk, S. W. (2021). Characteristics and Added Value of Fortified Sago Analog Rice Enriched with Nutritious Fish Oil Supplement. *IOP Conference Series: Earth and Environmental Science*, *934*(1), 012025. https://doi.org/10.1088/1755-1315/934/1/012025.

Tangke, U., Daeng, R. A., & Katiandagho, B. (2021). Organoleptic quality of tuna porridge canned with fortified tuna bone meal. *IOP Conference Series: Earth and Environmental Science*, *750* (1),012047. https://doi.org/10.1088/1755-1315/750/1/012047.

Turkmen, N., Senel, E., & Akal, C. (2019). Effect of Using Odourless Fish Oil on Some Physical, Chemical and Sensorial Properties of Blackberry Fruit Yoghurt. *Atatürk University Journal of Veterinary Sciences*, *14*(2), 142-150. https://doi.org/10.17094/ataunivbd.538769.

Unnikrishnan, P., Puthenveetil Kizhakkethil, B., Anant Jadhav, M., Sivam, V., Ashraf, P. M., Ninan, G., & Aliyamveetil Abubacker, Z. (2020). Protein hydrolysate from yellowfin tuna red meat as a fortifying and stabilizing agent in mayonnaise. *Journal of Food Science and Technology*, *57*(2), 413-425.

Unnikrishnan, P., Kizhakkethil, B. P., Jadhav, M. A., Sivam, V., Ashraf, P. M., Ninan, G., & Abubacker, Z. A. (2021). Characterization of Health Beverage Fortified with Peptides from Yellowfin Tuna. *Journal of Aquatic Food Product Technology*, *30*(9), 1142-1158. https://doi.org/10.1007/s13197-019-04069-x.

Weaver, C. M. (2014). Calcium supplementation: is protecting against osteoporosis counter to protecting against cardiovascular disease. *Current Osteoporosis Reports*, *12*, 211-218. https://doi.org/10.1007/s11914-014-0208-1.

Yarnpakdee, S., Benjakul, S., Kristinsson, H. G., & Maqsood, S. (2012). Effect of pretreatment on lipid oxidation and fishy odour development in protein hydrolysates from the muscle of Indian mackerel. *Food Chemistry*, *135*(4), 2474-2482. https://doi.org/10.1016/j.foodchem.2012.07.037.

Ye, A., Cui, J., Taneja, A., Zhu, X., & Singh, H. (2009). Evaluation of processed cheese fortified with fish oil emulsion. *Food Research International*, *42*(8), 1093-1098. https://doi.org/10.1016/j.foodres.2009.05.006.

Yin, T., Du, H., Zhang, J., & Xiong, S. (2016). Preparation and characterization of ultrafine fish bone powder. *Journal of Aquatic Food Product Technology*, *25*(7), 1045-1055. https://doi.org/10.1080/10498850.2015.1010128.

Yurko-Mauro, K., McCarthy, D., Rom, D., Nelson, E. B., Ryan, A. S., Blackwell, A., Salem Jr., N., & Stedman, M. (2010). Beneficial effects of docosahexaenoic acid on cognition in age-related cognitive decline. *Alzheimer's & Dementia*, *6*(6), 456-464. https://doi.org/10.1016/j.jalz.2010.01.013.

Zakaria, K. A., Yatim, N. I., Ali, N. A., & Rastegari, H. (2022). Recycling phosphorus and calcium from aquaculture waste as a precursor for hydroxyapatite (HAp) production: a review. *Environmental Science and Pollution Research*, *29*(31), 46471-46486. https://doi.org/10.1007/s11356-022-20521-6.

Zimmermann, M. B. (2009). Iodine deficiency. *Endocrine Reviews*, *30*(4), 376-408. https://doi.org/10.1210/er.2009-0011.