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REVIEW ARTICLE

Health benefits of fish oil and the application of encapsulated fish oil in meat and dairy products

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ABSTRACT

Fish oil is widely recognized for its health benefits, which are attributed to its high content of unsaturated fatty acids, notably docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA). Numerous clinical studies have demonstrated the positive impact of n-3 fatty acids on various health conditions, including cardiovascular disease and diabetes. However, despite benefits, dietary intake of n-3 fatty acids often falls below recommended levels. Given the widespread consumption of meat and dairy products, enriching these foods with fish oil presents a promising strategy for increasing dietary PUFA intake. The incorporation of fish oil into food products can be achieved through direct addition, emulsion, or encapsulation techniques. Encapsulation technology offers a promising solution by enhancing the oxidative stability of fish oil and mitigating undesirable fishy flavors & odours in the final product. This article will explore the health benefits of fish oil, discuss various methods for incorporating fish oil into foods and evaluate the potential of encapsulated fish oil in meat and dairy products.

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Introduction

Fish oil is the main source of *n*–3 long chain polyunsaturated fatty acids (PUFAs), such as eicosapentaenoic acid (20:5*n*–3, EPA) and docosahexaenoic acid (22:6*n*–3, DHA), in the human diet. Fatty acids are essential components that facilitate the structural integrity of cells, tissues, and organs. In addition to their structural role, they serve as the fundamental building blocks for various bioactive ingredients. Studies have shown that n-3 PUFAs not only decrease the risk of heart diseases but also exhibit anti-inflammatory properties and may reduce the risk of certain cancers and diabetes (Damerau et al., 2022; Patel et al., 2022). However, dietary intake of n-3 PUFAs is below recommended levels, despite its health benefits. A primary contributing factor to this situation is the prevalence of saturated fat in modern diets. The primary

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sources of saturated fatty acids (SFAs) are red meat and high-fat dairy products. The preponderance of saturated fat in the diet is largely attributable to cheese, milk and milk products, meat, fats (hard/solid), and butter (Perna & Hewlings, 2023). SFAs typically comprise nearly half of the total fat content in meat, with meat representing approximately half of the maximum recommended intake of SFAs (Geiker et al., 2021). The World Health Organization (WHO) has expressed support for research initiatives aimed at replacing SFAs in meat products (López-Pedrouso et al., 2021). In order to meet the daily requirements of essential PUFAs through dietary intake, there is a necessity for increased food fortification strategies. A viable option to avoid losing the benefits provided by PUFA is to protect their integrity by using appropriate encapsulating technologies. The encapsulation process is defined as the coating technique of small capsules of solids, gases, and liquids. This process offers several advantages, including protection of the encapsulated materials from oxidation, improvement of the stability of the oil, and extension of its shelf life. Additionally, it enables the controlled release of the encapsulated materials at specific rates (Badr et al., 2020; Selim et al., 2021; Rahmani-Manglano et al., 2024) Given their widespread global consumption, meat and dairy products appear to be promising candidates for such fortification efforts. This study elucidates the effects of fish oil on health and the efficacy of the technique of utilizing it in encapsulated form in meat and dairy products, as well as its effects on product properties.

Fish Oil

The Food and Agriculture Organization of the United Nations (FAO) has reported a consistent increase in the total production of fisheries over the past several decades. From 1950 to 2022, the production of live weight equivalent fisheries increased from 19 million tons to over 185 million tons, exhibiting an average annual growth rate of 3.2% (FAO, 2024). Only 40% of the catching fisheries is utilized for human consumption, and the remaining 60% is wasted (Rohim et al., 2024). Fish oil can be produced from whole fish or by-products from fish processing. The primary products derived from the valorization of fish manufacturing by-products are fish meal and fish oil (Rohim et al., 2024). Fish by-products consist of oil ranging from 1.40% to 40.10%, which depends on the species and tissue type. The economic value of fish oil has exhibited a marked increase day by day (Kalkan et al., 2025). Fish oil is main source of long-chain n-3 PUFA and contain docosahexaenoic acid (DHA; 22:6n-3) and eicosapentaenoic acid (EPA; 20:5n-3). The majority of commercially available fish oils have a 2:1 ratio of EPA to DHA.

In consideration of the abundant fatty acids it contains, fish oil is recommended by numerous health authorities around the world. More specifically, they recommended intake for n-3 fatty acids particularly EPA and DHA. The following Table 1 illustrates a selection of global n-3 PUFA intake recommendations.

Table 1. Global n-3 PUFA intake recommendations

Organization / Impact Area	Organization Type	Consumption Advice	Fatty Acid Type	Publication Date
Ministry of Health of The Republic of Türkiye General Directorate of Public Health - Healthy Nutrition and Active Life Department / Türkiye	Governmental Health Ministry	1g /day	EPA+ DHA	2019
GOED n-3	Global n-3 association	Adult: 500 mg/day Pregnant or lactating woman: 700 mg/day	EPA+DHA	2014
European Food Safety Authority (EFSA) / Europe	Authoritative body	Adult: between 250 and 500 mg/day	EPA+DHA	2014
The French Agency for the Safety of Health Products (AFFSA) / France	Authoritative body	500 mg / day 250 mg/ day 250 mg/day	EPA +DHA EPA DHA	2010
International Society for the Study of Fatty Acids and Lipids (ISSFAL) / Global	Expert scientific organization	Adult: at least 500 mg/day	EPA+DHA	2004
Scientific Advisory Committee on Nutrition (SACN) / United Kingdom	Authoritative body	0.45 g / day	n-3 PUFA	2004
World Health Organization (WHO) / Global	Authoritative body	1-2% energy of day	n-3 PUFAs	2003

It is noted that the high presence of these long-chain PUFAs makes n-3 oils susceptible to oxidation (Kolanowski, 2024; Kalkan et al., 2025). Due to its susceptibility to oxidation, the use or ingestion of fish oil for the purpose of obtaining nutritional benefits presents a significant difficulty. This challenge can be addressed through various approaches, including the addition of antioxidants such as, vitamin C, vitamin E, and polyphenols. Moreover, the presence of undesirable flavors and odors in fish oil presents a significant challenge for its utilization in the food processing industry. Because the structure of ω-3 PUFAs contains a large number of carbon-carbon double bonds, it is easily affected by oxygen, light, and heat during processing and storage, as a result of oxidative composition into a large number of unstable and easily decomposed undesirable volatiles (Sun et al., 2022). Presently, using nano-, micro-, and encapsulation methods has made it possible to keep fish oil's nutritional value while concurrently impeding its oxidation and the concomitant release of undesirable odors and flavors (Jamshidi et al., 2020). Apart from that, the addition of flavorings can be an effective solution to overcome the fishy taste and odours, thereby increasing the consumer acceptance of products include fish-oil.

Importance of n-3 PUFAs for Human Health

Fatty acids (FA) are carboxylic acids composed primarily of a long, unbranched hydrocarbon chain with an even number of carbon atoms. The majority of fats in foods are triglycerides, defined as a single glycerol unit combined with three fatty acid molecules. The classification of fatty acids based on the degree of unsaturation (presence of double bonds) leads to the identification of three classes: Saturated fatty acids or briefly SFA, Monounsaturated fatty acids or briefly MUFAS, and Polyunsaturated fatty acids or briefly PUFAS (Lima et al., 2022). According to the guidelines established by the World Health Organization (WHO), the proportion of total energy derived from total fat intake should not exceed 30%, while the intake of saturated fatty acids (SFA) should not surpass 10%. Additionally, the recommendation is to prioritize the consumption of polyunsaturated fatty acids (PUFA), with an intake that constitutes more than 6% of total energy. Limiting total fat intake and replacing SFA intake with polyunsaturated fatty acids (PUFA) could be a solution to reducing various diseases (Badar et al., 2021). The nutritionally important PUFAs for human health are n-3 and n-6 groups. Both omega families include different forms of fatty acids (Mariamenatu & Abdu, 2021). PUFAs are vital to the human body; however, an excessive consumption of n-6 over n-3 has been demonstrated to have detrimental consequences on human health, contributing to the development of numerous contemporary chronic inflammatory diseases, cardiovascular diseases, and some types of cancer. The optimal n-6/n-3 fatty acid ratio to achieve beneficial health effects is a matter of variation among institutions and countries. The optimal n-6/n-3 ratio values proposed by Canada, the Food and Agriculture Organization of the United Nations, and the Chinese Nutrition Society (2000) were 4–10, 5–10, and 4–6, respectively. In general, the n-6/n-3 ratio should not exceed 5 (Mariamenatu & Abdu, 2021; Cao et al., 2024). n-3 and n-6 both cannot be producing by human body and recognized as essential fatty acid n-3 and n-6 fatty acids have been approved as a therapeutic tool for the prevention of several health hazards globally (Kapoor et al., 2021). n-3 PUFA intake has beneficial effects on pregnant woman's mental health. It is recommended that women obtain a sufficient amount of n-3 PUFA during pregnancy, whether through dietary choices such as fish and seafood or through nutritional supplements (Tung et al., 2023). n-3 PUFAs have been demonstrated to enhance the proliferation of beneficial bacteria, including *Bifidobacterium,* in the gastrointestinal tract (Fu et al., 2021). n-3 polyunsaturated fatty acids (PUFAs) can play a pivotal role in the host's defense against infections. This function is attributed to the ability of n-3 PUFAs to limit excessive inflammation and to enhance immune responses (Husson et al., 2016). The presence of high levels of n-3 fatty acids in foodstuffs has been demonstrated to exert a positive influence on the human condition, particularly with regard to cardiac, cerebral, and nervous system function (Jamshidi et al., 2020). Table 2 presents some research findings investigated the relationship between the intake of n-3/PUFAs and the various diseases.

In the context of fish oil, the primary product that comes to mind is fish oil supplements. Globally, fish oils are among the most prevalent dietary supplements. In the United States, 17.7% of adults take dietary supplements, and of those, over one-third are fish oil supplements (Jairoun et al., 2020). Nutritional supplements contain EPA and DHA from fish oils, derived from anchovy, tuna, and cod liver (Sprague et al., 2018). Nonetheless, a considerable proportion of dietary supplements containing EPA and DHA available on the market contain lower amounts of these components than indicated on the labeling (Bannenberg et al., 2020). Study from Türkiye investigated that most of the 15 commercial fish oil on the Turkish market. Result showed that label claims for EPA were reasonably accurate for the products studied, but that DHA levels in some supplements differed significantly from the labels (Karsli, 2021). Another study conducted in France found that the total n-3 content of 2.5% of the samples examined did not correspond to the content indicated on the labeling of the products (Pasini et al., 2022). Given the potential for misleading content, this calls for further investigation into the competence of these fish oil supplements.

Table 2. Summary of some research findings of relationship between n-3/ PUFAs intake and various diseases

Findings	Number of Participants	Number of Reported Cases After Experiment	Reference
Insulin sensitivity was enhanced in type 2 diabetic patients who received supplementation of n-3 polyunsaturated fatty acids (PUFA)	44	No follow-up	Farsi et al. (2014)
The ingestion of tuna and dark fish, as well as α-linolenic acid (ALA) and marine/fish n-3 acids (PUFAs), was associated with a reduced risk of major cardiovascular disease (CVD) in women without a history of CVD.	713,559 (women)	A total of 1,941 cases of major cardiovascular disease (CVD) were documented, including instances of myocardial infarction (MI), stroke, and cardiovascular death.	Rhee et al. (2017)
Fish intake and n-3 PUFA associated with reduced risk of psychological distress in women during and after pregnancy.	• 75,139 pregnancies in the first trimester • 79,346 pregnancies in the second or third trimester • 77,661 pregnancies in the postpartum period.	No follow-up	Hamazaki et al. (2018)
Patients with high intake of fish oil n-3 PUFAs demonstrated prolonged disease-free survival. It was observed that patients who ingested marine-source n-3 on a weekly basis exhibited a 35% reduced risk of cancer recurrence or mortality in comparison with those who did not consume.	1011 colon cancer patients	343 patient colon cancer recurrences and 305 patients died.	Van Blarigan et al. (2018)
Higher concentrations of EPA were associated with a lower risk of incident Alzheimer Disease. This study results supports a beneficial role of n-3 PUFAs for cognitive health in old age.	1264 healthy participants aged 84 ± 3 years	For 7 years follow-up time 233 participants developed dementia	Van Lent et al. (2021)
n-3 PUFA consumption augmented the reduction of abdominal fat mass and percentage in overweight or obese individuals on a weight loss diet.	40 Adult	No follow-up	Salman et al. (2022)
Dietary intake of n-3 fatty acids could lower risk of all-cause dementia or cognitive decline by ~20%, especially for docosahexaenoic acid (DHA) intake	1135 participants without dementia	No follow-up	Wei et al. (2023)

Food Product Enrichment Techniques With Fish Oil

Notwithstanding the substantial health benefits associated with fish oil, its utilization within the food industry is constrained by several factors. Such limitations include its low solubility, susceptibility to oxidation, the presence of an undesired fishy flavor, and suboptimal handling properties (Jamshidi et al., 2020). The direct addition of fish oil, the emulsification of fish oil, and the encapsulation of fish oil techniques are the most commonly used methods for adding fish oil to fortified foods.

Direct oil addition is basic method for enriched food products. However, it is not suitable for food products in many ways. The direct addition of oil to food products has been revealed to possess a number of significant drawbacks, including an increased susceptibility to oxidation reactions, a reduced solubility, and an elevated hardness, which is attributed to the formation of smaller fat globules (Badar et al., 2021). It was suggested that bulk fish oil should be used with antioxidants in food products to prevent fish oil oxidation and reduce lipid hydroperoxides, which influence the profile of volatiles and develop unpleasant off-odors and off-flavors (Drusch et al., 2008). For instance, regarding enriching meat products with bulk/direct fish oil, EPA and DHA are significantly increased. However, the increase in lipid oxidation, accompanied by the resulting changes, such as undesirable taste and odor, led to the limited use of this technique in industry (Drusch et al., 2008; Serfert et al., 2010; Pérez-Palacios et al., 2019).

Emulsification constitutes another technique for enriching food products with fish oil. An emulsion is defined as a mixture of two immiscible liquids, typically water and oil, wherein one liquid is dispersed in the other (Kim et al., 2021). Conventional emulsions can be classified into two primary categories: oil-in-water (O/W) and water-in-oil (W/O) emulsions. Common fish oil emulsions are of the oil-in-water (O/W) type. Fats are crucial for maintaining water-holding capacity, forming stable emulsions, and enhancing emulsion stability (Shin et al., 2019). The fortification of food products can be achieved through the direct incorporation of fish oil emulsions, for instance, in meat systems or beverages. However, several challenges are associated with substituting animal fats with emulsion oils in meat products. Primarily, the hydrophilic nature of meat presents a challenge in the incorporation of hydrophobic oils. Secondly, increasing the unsaturated fatty acid (UFA) content can heighten susceptibility to lipid oxidation, thereby reducing shelf-life (Yıldız Turp & Serdaroglu, 2012). To ensure product stability, oils must be effectively emulsified within the myofibrillar protein matrix or with the aid of exogenous emulsifiers (Bolger et al., 2017). The addition of fish oil emulsion to dairy products can increase oxidation, adversely affect sensory quality and alter microstructure. The type of emulsion used can influence oxidative stability, with combinations of milk proteins and phospholipids. Conflicting results observed in different dairy products limit the ability to draw definitive conclusions about the effects of emulsified fish oil. Therefore, in industry when manufacturing dairy products with added fish oil, a multi-faceted approach to minimizing oxidation should be considered, including the use of different emulsion types, the incorporation of antioxidants, and the evaluation of different forms of fish oil (Horn et al., 2012). There are still relatively few types of fish oil emulsion systems. Existing delivery systems for fish oil emulsions have become obsolete due to their inability to meet the evolving demands for enhanced nutritional and health benefits. Therefore, new emulsion systems need to be developed (Chen et al., 2024). Alternatively, the emulsions can undergo processing into microcapsules. Encapsulated fish oil is a promising technique prior to its incorporation into food products. The food industry utilizes encapsulation for a variety of purposes, including the concealment of undesirable odors, flavor, or taste, the preservation of bioactive components, the addition of functional and nutritional elements, and the controlled release of encapsulated components at a designated location, time, and rate (Kumar et al., 2024). Encapsulation of fish oils prevents oxidation of polyunsaturated fatty acids, thus preventing loss of nutritional value and deterioration of taste (Soyuçok et al., 2019).

Fish Oil Encapsulation Methods

Macroencapsulation

Macroencapsulation and encapsulation are related but distinct techniques that differ primarily in their scope and application. Macroencapsulation is a sub-technique of encapsulation, the broader category of which encompasses a variety of encapsulation techniques. Macroencapsulation involves the creation of capsules of a larger size than microencapsulation and nanoencapsulation. Generally, the size of macrocapsules is 2 mm or more (Korkmaz & Tunçtürk, 2024). The primary application of macroencapsulation pertains to the domain of food ingredients and supplements. In comparison to nano and microencapsulation techniques, macroencapsulation typically elicits a lower degree of toxicity concerns due to its larger capsule size. This method often employs natural and edible coatings, such as gelatin, waxes, or gum coatings, which are relatively safe (Rezagholizade-Shirvan et al., 2024). The larger size of macrocapsules enhances visual appeal and consumer attraction, particularly when the capsule itself is a key aspect of the product experience. Moreover, the shell can be designed to rupture easily, facilitating rapid and significant release of the active ingredient, which is advantageous in applications requiring a sudden and intense effect, such as flavor release in chewing gum (Ngamnikom et al., 2017). A review of the extant literature reveals an absence of studies addressing the macroencapsulation of fish oil. This paucity of research may be attributed to the prevailing perception that alternative encapsulation methods are more appropriate, given its distinct taste and odor.

Microencapsulation

Microencapsulation is another specific technique within the broader category of encapsulation. It involves the encapsulation of ingredients into microspheres, microcapsules or microparticles, with a focus on protecting these substances and enhancing their delivery (Subasri et al., 2024; Thakur et al., 2024). A microcapsule is defined as a minute, spherical particle with a diameter ranging from 50 nanometers to 2 millimeters. These particles can assume diverse forms, including hard or soft gelatin or liquid suspension. Microcapsules are characterized by their dispersion within a solid matrix devoid of a discernible outer wall phase, in addition to intermediate forms, as well as particles or droplets encased within a membrane. The composition of a microcapsule is divided into two fundamental components: the core material and the coating/wall material. The core material is defined as the material to be coated. The coating/wall material is the material that is placed on the core material, thereby imparting thickness to it. The coating material should permit the release of the core material under specific circumstances without reacting with the core material (Bower et al., 2024). The process of microencapsulation has several notable benefits to fish oil. Firstly, it has been shown to enhance the oxidation stability of the oil. Secondly, microencapsulation has been demonstrated to reduce the intensity of the fishy odor characteristic of fish oil. Moreover, microencapsulation has been shown to render the oil suitable for incorporation into various food products (Yeşilsu, 2023). A multitude of methodology exists for the preparation of microcapsules. Spray drying is still the most widely used microencapsulation technique. It is still one of the most preferred method of microencapsulation in various food industries due to lower cost of production and requirement of less sophisticated set up. It is highly automated, cost effective and produces a good quality product. Other microencapsulation techniques including fluidized bed coating, extrusion, cocrystallization and liposome-entrapment impart great stability to food ingredients in the dry state but release their content readily only the encapsulated product is exposed to high water activity environment (Timilsena et al., 2020). Liposome-entrapment is successful to deliver their content in special conditions. However, the primary challenge associated with this method pertains to the expansion of the microencapsulation process to a commercial scale (Desai & Park, 2005). Other encapsulation methods include interfacial polymerization, organic phase separation, molecular inclusion, coacervation, freeze drying, spray drying, spray chilling, microfluidic jet, electro-spraying, and electrospinning (Noore et al., 2021; Gültekin Subaşı et al., 2021; Yan & Kim, 2024).

Study by Yang et al. (2024a) investigated the effect of spray drying (SD), spray freeze-drying (SFD), freeze-drying (FD), and microwave freeze-drying (MFD) on the characteristics of fish oil microcapsules. According to their results, the microencapsulate fish oil prepared with SD yielded the highest encapsulation efficiency (86.98%), followed by SFD (77.79%), FD (63.29%), and MFD (57.89%). The higher efficiency of spray drying can be attributed to the liquid film it generates during the drying process. In regard to the fatty acid composition of the samples, the spray drying technique yielded the highest levels of total PUFA. The percentages of EPA were as follows: Fish oil (16.86%), SD (12.83%), SFD (12.52%), FD (10.54%), and MFD (11.73%). The DHA percentages were as follows: Fish oil (11.87%), SD (7.28%), SFD (6.63%), FD (5.55%), and MFD (7.52%). A comparison of uniaxial or coaxial electrospraying and spray drying of fish oil showed that spray drying produced larger capsules with higher encapsulation efficiency (EE > 84%), while uniaxial electrospraying produced submicron capsules with EE 69-72%. Coaxial electrospraying had the lowest EE (53-59%). For spray drying and monoaxial electrospraying, the EE is closely related to its physical stability. As a result, coaxial electrospraying had the lowest oxidative stability among the techniques studied (Rahmani-Manglano et al., 2023).

Study conducted by Jokar et al. (2024) investigated fish oil microencapsulated by using Arabic gum (AG) and Persian gum (PG) as wall materials. Optimal microencapsulation of fish oil was achieved using a 26:4 gum Arabic-gum Persian blend, a 4:1 wall-to-oil ratio, 210°C drying temperature, and a high feed flow rate. Microencapsulation efficiency (79.49%), low moisture content (3.39%), low peroxide value (10.98 meq O2/kg oil), and a relatively small particle size (39.05 µm), indicating good oxidative stability and potential for increased storage life. The Microencapsulation Efficiency (MEE) of 79.49% achieved in this study is reported notably high compared to values reported in previous literature. The low moisture content (MC) of 3.39% is mentioned as advantageous for long-term storage, as lower moisture levels generally reduce the risk of microbial growth and spoilage.

Nanoencapsulation

Nanotechnology has emerged as a highly promising technological approach with the potential to transform conventional food science and the food industry. The process of nanoencapsulation entails the encapsulation of small particles of core materials (in this case, fish oil) within a wall material or encapsulant, with a nanometer size (smaller than 1 µm/0.001 mm) (Silva Sales et al., 2023). The selection of nanoencapsulation method is contingent upon the type of core material to be encapsulated and the polymer utilized as the encapsulant or wall material. The available techniques encompass nanoprecipitation, gelling *via* ionic emulsification, emulsion–diffusion, and emulsification–evaporation of the solvent (Ferreira & Nunes, 2019). Important sign of success of nanoencapsulation is encapsulation efficiency (EE). İt refers to the amount of oil contained in the nanoparticles, which is related to the nanoparticle's stability and protection against oxidation. EE values ranging from 60% to 80% were identified in fish oil nanoparticles produced by homogenization, while values exceeding 80% were observed in fish oil nanoparticles derived from ultra-sound, nanoprecipitation, and low-energy self-emulsification methodologies (Ilyasoglu & El, 2014). The choice of emulsifier can also determine the efficiency of nanoencapsulation. Tween 80 was the main emulsifier used for both edible and essential oils nanoparticles, followed by Tween 20 (Silva Sales et al., 2023). The wall material is another important parameter. In their study, Raeisi et al. (2019) nanoencapsulated fish oil and garlic essential oil using various percentages of chitosan and Persian gum-chitosan. The results showed that the 2:1 w/w ratio of Persian gum and chitosan will offer the best performance of nanoencapsulated fish oil-garlic oil for use in the food industry. Current studies highlight that nanoencapsulation may be a solution to overcome the limitations of fish oil in food applications. Nanoencapsulation has demonstrated efficacy in preserving the integrity of ingredients by mitigating the effects of evaporation, oxidation, light-induced reactions, and degradation due to exposure to heat and moisture. Nanoencapsulation technique can mask undesirable flavors and enhance solubility and sensory characteristics (Sun et al., 2021).

The Impact of Encapsulated Fish Oil on Meat Products

Meat and meat products are essential part of the human diet. Meat is a primer source of essential amino acids and supplies amino acid derived metabolites and peptides that have important bioactive properties (Geiker et al., 2021). Meat and meat products, such as sausages, meatballs, meat cakes, and various other local delicacies, consistently enjoy high market demand. These products are highly valuable for consumers, mainly due to their sensory properties (Liu et al., 2024). Despite their importance as a source of high-quality proteins and certain vitamins (most notably vitamin B6 and B12) and minerals (including iron, selenium, and zinc), the lipid profile of meat and meat products is nutritionally deficient. Meat and meat products contain high amount of SFAs and low PUFA contents and to the higher content in n-6 PUFA than in n-3 (Pérez-Palacios et al., 2019). High consumption of (SFAs) is associated with various diseases and health problems, especially cardiovascular disease (CVD). A reduction in the consumption of SFAs has been indicated as a factor associated with a considerable decrease in the risk of CVD (Te Morenga & Montez, 2017). Different strategies focused on enhancing the lipid profile of meat and meat products have been evaluated. It has been stated that the use of different encapsulated unsaturated fatty acids in place of animal fat in fermented meat products does not pose a technological challenge and contributes to the development of health-promoting foods (Soyuçok et al., 2019). Although different alternatives are being investigated to improve the fat profile, one of the strongest candidates is encapsulated fish oil due to its rich n-3 PUFA content and minimum effect on sensory attributes. The addition of encapsulated fish oil to meat products has the potential to improve their structural attributes and sensory characteristics. In the studies carried out, it was observed that the incorporation of encapsulated fish oil into meat products with different characteristics did not generally have a negative effect on the sensory properties of the product. This situation demonstrates the importance of the encapsulation technique in preventing the negative sensory properties that occur when fish oil, which has a uniquely strong flavor and odour, is used directly in products.

Table 3. Advantages and disadvantages of encapsulation techniques

Advantages	Disadvantages
Encapsulation techniques allow for sustained and targeted material delivery	The development of stable and effective encapsulated products can be complex and is a matter of extensive optimization
Encapsulation technology protects sensitive compounds from the effects of external factors	Other newly developed technologies, with the exception of spray drying, may be difficult to adapt to the industry
Encapsulation can mask unpleasant flavors and odors	Advanced encapsulation methods can be expensive
Maintains stability of bioactive compounds during processing and storage	Some encapsulation techniques require complex equipment's
Advance encapsulation techniques have strong control over particle size and morphology, allowing different formulations to be achieved with particles of desired size	Some encapsulation techniques can involve complex post-processing purification steps
Encapsulation has been demonstrated to extend the shelf life of components	Encapsulation include freeze drying, hot air fluidized bed, and flash drying etc. require high energy consumption

Note: References are Abdul Mudalip et al. (2019); Ozkan et al. (2019); Abdul-Al et al. (2023); Thakur et al. (2024).

Study revealed by Stangierski et al. (2020) investigated the effect of adding microencapsulated fish oil powder to chicken sausages on mechanical, structural and sensory properties. Microencapsulated fish oil powder (ME) improved the textural properties of chicken sausages, such as hardness, gumminess, chewiness and water activity. The sensory evaluation results indicated that there were equal ratings for the external color and the color of the cross section of all samples. The sausages products with microencapsulated fish oil powder (ME) were rated highest for their consistency (the thickest), especially when heated. As a result of storage sensory analysis, the most attractive sausages on the first and 21st day of storage were the sample with microencapsulated fish oil powder. Another study investigated the fatty acid profile poultry sausages with ME and liquid fish oil. Interactive effects were observed between the type of fish oil and storage time, on the EPA and DHA content. Researchers have indicated that it is quite challenging to specifically determine EPA and DHA in microencapsulated fish oil, and that their distribution in the product cannot be tracked. As a result, this study proposed liquid fish oil than microencapsulated fish oil for poultry sausages (Kawecki et al., 2021). The composition of wall material is one of the important parameters in the encapsulation. Pourashouri et al. (2021) investigated the impact of wall material (tragacanth (TRG) and carrageenan (CGN) on fish oil microencapsulation and its subsequent incorporation into chicken nuggets. Samples prepared respectively: Control -chicken nuggets with no fish oil, FOL-chicken nuggets with added free fish oil (1%), TRG-chicken nuggets containing fish oil encapsulated with tragacanth, CGN-chicken nuggets with fish oil encapsulated with carrageenan. TRG microcapsules provide a slightly higher level of protection for EPA and DHA during storage. EPA+DHA mg/g samples values are respectively: Control 0.05 mg/g, FO 2.01 mg/g, TRG 2.04 mg/g, CGN 2.02 mg/g. Also, TRG were found to be closer to the control group in terms of sensory characteristics (texture, crustiness, oiliness, juiciness, hardness, taste, flavor, and fish odor). TRG was found to be a more effective wall material than CGN in encapsulating fish oil and preserving nugget quality.

The microencapsulation of fish oil can be accomplished through the creation of monolayered (Mo) or multilayered (Mu) emulsions, each of which offering different properties and influencing the application of these encapsulated oils in meat products differently. Study of Solomando et al. (2020) evaluated the use of (Mo) and (Mu) fish oil microcapsules in cooked and dry-cured sausages. Monolayered and multilayered emulsions of fish oil were spray-dried to obtain their corresponding microcapsules (designated as Mo and Mu, respectively). Two distinct sausage products were prepared: cooked (C-SAU) and dry-cured sausages (D-SAU). In both sausages evaluated, the amount of EPA and DHA increased from the control (mentioned as not detected) to the fortified batches. Two sample group showed no significant differences between Mo and Mu enriched products in C-SAU (0.16 and 0.15 mg EPA/g sample and 0.31 and 0.32 mg DHA/g sample, respectively) and D-SAU (0.17 and 0.19 mg EPA/g sample and 0.39 and 0.42 mg DHA/g sample, respectively). In conclusion, the study demonstrated that both monolayer and multilayer fish oil microcapsules can be successfully incorporated into meat products to enhance their n-3 fatty acid contents. However, further sensory analysis is recommended, particularly to investigate the effects of storage duration and microcapsule type on sensory quality. A study of chicken nuggets containing encapsulated fish and garlic oil revealed that the use of 8% (w/w) encapsulated fish oil-garlic oil provided the optimal antioxidant and antimicrobial properties during storage. However, sensory analyses indicated that 4% (w/w) encapsulated fish oil added sample was more acceptable, in terms of overall acceptability, taste, and odor, during storage (Raeisi et al., 2021). Given the considerable variance in the optimal ratio of encapsulated fish oil to meat product, which is dependent on the specific product and its desired properties, it is not feasible to offer a generalized recommendation for all products.

The Impact of Encapsulated Fish Oil on Dairy Products

Dairy products are significant dietary sources of essential nutrients, including protein, fat, vitamins, and minerals, contributing to their widespread global consumption. Cow milk is a rich source of fat, lactose, protein with a high biological value, minerals relevant for skeletal growth like calcium, phosphorous, magnesium, and several trace elements and vitamins like zinc, iodine, vitamins B2, B12, D, and A. Given dairy-based products extensive consumption across all age groups and their critical role in human nutrition, dairy products are important categories for enhancing fatty acid content through the incorporation of fish oil. Dairy-based foods can be categorized into three groups: liquid (milk and fermented milk products), semi-solid (yogurt & certain soft cheeses and ice-cream), and solid (primarily cheeses) (Scholz-Ahrens et al., 2020; Qazi et al., 2024). A variety of encapsulation methods such as emulsification, coacervation, spray/freeze-drying, and liposomes are available for encapsulation of oil in dairy products. Nevertheless, it must be acknowledged that a single method is not generally applicable to all purposes and products. The optimal encapsulation technique must be selected with consideration for the bioactive characteristics, such as molecular structure, polarity, molecular weight, and solubility, as well as the physicochemical properties of the dairy matrix. Suitable wall materials should be selected for the encapsulation of bio actives towards their incorporation into milk and dairy products (Adinepour et al., 2022). Nanoencapsulated fish oil, comprising n-3 fatty acids, was incorporated into a probiotic fermented milk product. The results of study demonstrated that the incorporation of nanoencapsulated fish oil led to an increase in probiotic bacterial counts decreased the oxidation of EPA and DHA without any adverse effects on the sensory attributes of the product (Moghadam et al., 2019). Another study on milk investigated the encapsulation of fish oil in hollow solid lipid micro and nanoparticles (HoSoLiP) followed by its incorporation into skim milk. Milk fortified with fish oil encapsulated with (HoSoLiPs) remained stable for 3 weeks, whereas milk enriched with direct fish oil exhibited a shorter shelf life, remaining stable for only 1 week. These findings demonstrate that the incorporation of fish oil-loaded HoSoLiPs into milk represents a novel approach for enriching dairy products with n-3 fatty acids (Yang et al., 2024b). The effects of fish oil and alternative microcapsule wall materials are being investigated in some studies. Mahfoudhi et al. (2022) tested the efficacy of almond gum as a new wall material for microencapsulating fish oil and used it to produce fortified yogurt. The results showed that the almond gum/gelatin mixture protected the fish oil from oxidation and masked the undesirable fishy odor and taste of the fortified yogurt. At the end of storage, yogurts containing microencapsulated fish oil retained more n-3 fatty acids (ME 82%, CO 67%) The effect of nanoencapsulated fish oil on the physicochemical properties and sensory quality of yogurt was investigated by researchers. Nanocapsule fish oil were incorporated into yogurt at 15mL/100 g. The results demonstrated an increase in the stability of n-3 fatty acids, such as DHA and EPA, with high sensory acceptability (Ghorbanzade et al., 2017). Another study investigated to develop functional yoghurt with encapsulated fish oil using the nanoemulsion technique as n-3 source. The sample containing nanoemulsion encapsulated fish oil was found to retain 71.75% of its fatty acid content during storage. The overall results show that the developed yoghurt showed significant improvements in both sensory properties and oxidative quality (Shanuke et al., 2025). The fortification of frequently consumed daily foods, such as yogurt, is importance in supporting the recommended amounts for health. In their study, Murage et al. (2021) stated that n-3-fortified yogurt is a source of n-3 fatty acids, providing a sufficient amount of heart-healthy nutrients to reach the recommended daily intake of 150 mg/day with a single serving (150 g) of yogurt.

Conclusion

Consumer's interest in enriched food products is increasing because they offer health benefits besides than food. Meat and dairy products are considered staple foods that are widely consumed across diverse geographical regions and cultural contexts. Fish oil is main source of PUFA and n-3 fatty acids. Many health authorities make recommendation regular intake for n-3 fatty acids particularly EPA and DHA. The presence of high levels of n-3 fatty acids in foods has positive influence on the human health condition to especially, cardiac, cerebral, and nervous system function. Consequently, fish oil is a substantial source of polyunsaturated fatty acids (PUFAs) and n-3 acids, which have been demonstrated to offer substantial health benefits. However, the daily intake of fish oil remains below the recommended levels. Enrichment food products with fish oil is important field that is the focus of significant research. The inherent susceptibility of fish oil to oxidation and its potential to negatively impact product sensory qualities, such as taste and odor, has necessitated the exploration of encapsulation technologies. While encapsulation offers significant potential for enhancing the functionality and quality of food products, several challenges remain. First, it should be noted that not all products or applications are suitable for encapsulation. Some products may not be able to withstand the encapsulation process, while others may not be compatible with the materials used. Second, the high cost of nano-/microencapsulation technology limits its industrial application. In addition, ensuring the uniform distribution of active ingredients and the effectiveness of microcapsules in protecting them from environmental factors during production and storage is a significant challenge. While a number of clinical trials have evaluated the impact of fish oil intake on human health, more research is needed to assess the specific health effects of consuming fish oil-enriched meat and dairy products. Further research endeavors should concentrate on enhancing encapsulation methodologies, contemplating cost-effectiveness, and meticulously appraising the health benefits of consuming fish oil-enriched food products in human populations.

Compliance With Ethical Standards

Authors' Contributions

GYT: Conceptualization, Supervision, Writing – review & editing

SÖ: Conceptualization, Investigation, Writing – original draft

All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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Data availability is not applicable to this article as no new data were created or analyzed in this study.

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The authors confirm that no generative AI was used in writing this manuscript or creating images, tables, or graphics.

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