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Trends in Microencapsulation of Lemuru Fish Oil for Child Nutrition: A Systematic Review of Oxidative Stability, Sensory Acceptance, and Fortification Opportunities in Cereal Products

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Abstract

Lemuru fish oil, rich in long-chain polyunsaturated fatty acids like EPA and DHA, is vital for children's growth and brain development. However, its chemical instability complicates its incorporation into food products. This review, adhering to PRISMA 2020 guidelines, analyzes microencapsulation technology for fish oil, focusing on preserving quality and flavor when added to foods such as cereals for young children. A search of Scopus and Elsevier yielded 19 relevant papers from 2015 to 2025. Various microencapsulation methods and coating materials were examined, revealing that complex coacervation with chitosan and proteins (encapsulation efficiency of 87-93%) and spray-drying techniques offer superior protection against oxidation. Taste studies suggest that incorporating fruit flavors and antioxidants mitigates the fishy flavor, enhancing consumer acceptance. Furthermore, microencapsulated Lemuru fish oil shows improved performance in digestion simulations, supporting its role in child nutrition programs. The review also points out gaps for future research to enhance microencapsulation for effective fortified cereals, especially in omega-3 deficient regions.

Keywords *- child nutrition, fish oil, omega-3 fatty acids, oxidative stability, sensory acceptance*

Abstrak

Minyak ikan lemuru, yang kaya akan asam lemak tak jenuh ganda rantai panjang seperti EPA dan DHA, sangat penting untuk pertumbuhan anak dan perkembangan otak. Namun, ketidakstabilan kimianya menyulitkan pengaplikasiannya dalam produk pangan. Tinjauan ini, yang mengikuti pedoman PRISMA 2020, menganalisis teknologi mikroenkapsulasi untuk minyak ikan, dengan fokus pada upaya menjaga kualitas dan cita rasa saat ditambahkan ke makanan seperti sereal untuk anak-anak. Pencarian literatur dari Scopus dan Elsevier menghasilkan 19 artikel relevan dari tahun 2015 hingga 2025. Berbagai metode mikroenkapsulasi dan bahan pelapis dikaji, yang menunjukkan bahwa teknik koaservasi kompleks dengan kitosan dan protein (efisiensi enkapsulasi 87–93%) serta metode spray drying memberikan perlindungan terbaik terhadap oksidasi. Studi sensori menunjukkan bahwa penambahan perisa buah dan antioksidan dapat mengurangi bau amis, sehingga meningkatkan penerimaan konsumen. Selain itu, minyak ikan lemuru yang dimikroenkapsulasi menunjukkan kinerja yang lebih baik dalam simulasi pencernaan, mendukung perannya dalam program nutrisi anak. Tinjauan ini juga mengidentifikasi kesenjangan penelitian untuk pengembangan mikroenkapsulasi yang lebih efektif dalam fortifikasi sereal, khususnya di daerah yang kekurangan omega-3.

Kata kunci *— nutrisi anak, minyak ikan, asam lemak omega-3, stabilitas oksidatif, penerimaan sensori*

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INTRODUCTION

The lemuru fish, also known as *Sardinella lemuru*, is one of the richest natural sources of long-chain polyunsaturated fatty acids. This fish's omega-3 content accounts for around 25 to 35 percent of the total fatty acids present. The main bioactive compounds, eicosapentaenoic acid (EPA; C20:5ω-3) and docosahexaenoic acid (DHA; C22:6ω-3), make up 12 to 18 percent and 8 to 12 percent of the total lipid content in lemuru oil, respectively.(Weiser & Alessandri, 2021),(Mun et al., 2021) These long-chain polyunsaturated fatty acids are considered conditionally essential nutrients during childhood, especially during the key periods of neural development that occur from the prenatal stage through early childhood.

The importance of EPA and DHA for brain development is significant. DHA makes up about 25% of the fats in the brain and 50% of the fats in the membranes of retinal cells, which means having enough DHA is crucial for good thinking, clear vision, and managing behavior.(Mun et al., 2021) Studies show that children who do not get enough DHA may have trouble with reading, shorter attention spans, more behavioral issues, and poorer school performance compared to children who receive sufficient amounts of this nutrient.(Weiser & Alessandri, 2021)

Despite its excellent nutritional benefits, lemuru fish oil poses significant challenges in food technology because it is very prone to lipid peroxidation. This occurs due to the high level of unsaturation in the EPA and DHA molecules, which have 5 and 6 double bonds respectively. These unsaturated bonds are easily attacked by free radicals, leading to autoxidation, especially when the oil is exposed to oxygen, heat, light, and transition metal catalysts that are often found in food processing environments.(Shen et al., 2022),(Aslam et al., 2023) The oxidation of omega-3 fatty acids first produces lipid hydroperoxides, which then break down into secondary oxidation products such as aldehydes, alcohols, and ketones. These volatile compounds, particularly 2,4-decadienal, 2,4-heptadienal, and hexanal, contribute to undesirable flavors that are often described as "fishy," "rancid," or "metallic."(Shen et al., 2022),(Berton-Carabin, Serfert, Van Den Heuvel, & Schwarz, 2020)

The World Health Organization and the International Society for the Study of Fatty Acids and Lipids suggest that children aged 1 to 8 years should consume at least 100 to 1500 mg of EPA plus DHA daily, while children aged 9 to 13 years should get 100 to 2000 mg daily. The highest levels within these ranges are linked to the best cognitive benefits. However, current data show that a large majority of children in developed countries—between 72% and 85%—and even more in developing regions 88% to 95% consume far less than these amounts. This creates a major nutrition gap.(Mun et al., 2021),(Gao, Margawati, & Gao, 2023) The problem is especially serious in areas where people mainly eat cereals and don't eat much seafood. In these developing regions, fortified cereals are the most practical and affordable way to provide omega-3s to a large population, as long as the microencapsulation technology used can keep the oils stable and maintain their taste and smell during production and storage.

Microencapsulation is a method where liquid or solid materials are surrounded by a protective layer made of polymers. This technique has been proven to help with the chemical instability of oils rich in omega-3 fatty acids.(Hamaguchi, Roudaut, Chambin, Voilley, & Saurel, 2021),(Choudhury, Meghwal, & Das, 2021) By creating a barrier between the oils and harmful elements in the environment, microencapsulation can significantly increase the shelf life of the product, from just a few weeks for regular oils to several months or even years for properly made microcapsules. It also helps hide any unpleasant tastes or smells through the formation of barriers and by adjusting the flavor.

LITERATUR REVIEW

This review is designed to : (1) thoroughly examine microencapsulation methods used to stabilize fish oil, with a focus on how efficiently and at what scale these methods can be applied in food manufacturing; (2) thoroughly evaluate the different types of wall materials used in microencapsulation and how they individually and together help in keeping the fish oil from oxidizing; (3) gather and summarize information on how well microencapsulated fish oil maintains its sensory qualities, such as its smell, and how well it is accepted by consumers when added to fortified cereals; (4) look into how well the omega-3 fatty acids in microencapsulated fish oil are released and absorbed by the body after going through simulated and real digestion processes; (5) explore practical ways to add microencapsulated fish oil to cereal products aimed at children, while considering factors like cost, following regulations, and ensuring environmental sustainability; (6) pinpoint areas where more research is needed and offer recommendations based on available evidence to improve the formulation of microencapsulation methods for large-scale use in fortifying lemuru fish oil.

METHOD

Protocol and Registration

This systematic review was carried out and presented following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines.(Page et al., 2021) The study protocol was registered in the PROSPERO database before starting the literature search. The research question was structured using the PICO framework, which includes: Population microencapsulation systems for fish oil used in child nutrition; Intervention microencapsulation technologies with different wall materials and processing parameters; Comparison various encapsulation methods, wall material compositions, and process conditions; and Outcomes oxidative stability (measured by peroxide value, TBARS, and volatile oxidation markers), sensory characteristics, encapsulation efficiency, particle size, bioaccessibility, and bioavailability.

Information Sources and Search Strategy

Comprehensive searches were carried out in the Scopus and Elsevier ScienceDirect databases for academic publications dated from January 1, 2001, to December 31, 2024. The search approach used Boolean operators and controlled vocabulary in this manner: ("microencapsulation" OR "encapsulation" OR "nanoemulsion" OR "complex coacervation" OR "spray drying" OR "spray-drying" OR "freeze drying" OR "electrospraying") AND ("fish oil" OR "omega-3" OR "EPA" OR "DHA" OR "PUFA" OR "polyunsaturated fatty acid" OR "lemuru" OR "sardine oil") AND ("oxidative stability" OR "oxidation" OR "peroxide" OR "rancidity" OR The search was narrowed to peer-reviewed journal publications written in English. All collected articles were then loaded into reference management software, specifically Mendeley, to remove duplicates and do preliminary screening.

Inclusion and Exclusion Criteria

The inclusion criteria covered peer-reviewed journal articles published between 2001 and 2025 in English; original research studies that provided empirical data on fish oil microencapsulation or other forms of omega-3 encapsulation; studies published in Scopus Q1 to Q4 and Elsevier journals; research that addressed at least one of the following outcomes: oxidative stability, sensory characteristics, encapsulation efficiency, or bioaccessibility and bioavailability; studies that included enough methodological details to allow for quality assessment; and research that could be applied in the context of food fortification. The exclusion criteria included review articles, opinion pieces, editorials, and conference abstracts that were not fully published; studies focused solely on pharmaceutical or clinical applications without relevance to food; non-English publications; studies with significant methodological limitations or incomplete data reporting; articles that described only theoretical models without empirical validation; and studies that used only artificial or non-food-grade materials as the encapsulation walls.

Study Selection Process

Title and abstract screening was carried out independently by two reviewers, with agreement between them measured using Cohen's kappa, which was at least 0.75. Articles that met the inclusion criteria were then subjected to a thorough evaluation. Any disagreements about whether an article should be included were addressed through group discussion or by seeking input from a third reviewer. The entire selection process was recorded in a flow diagram, following the PRISMA guidelines.

Data Extraction and Synthesis

Standardized data extraction forms collected the following details from each study: author names and the year of publication, country where the study was conducted, the type of study design used, the source or species of fish oil, the encapsulation technology applied, the composition of the wall material, and the processing conditions including temperature, pH level, mixing speed, and the ratio of oil to wall material. The outcomes of the studies were recorded with specific numerical values, along with measures of study quality. Oxidative stability was assessed using established metrics, including peroxide value, which is measured in milliequivalents of oxygen per kilogram of oil, with a defined acceptable threshold <5), thiobarbituric acid reactive substances (TBARS) and volatile oxidation markers were quantified using gas chromatography-mass spectrometry. Encapsulation efficiency was measured as a percentage of the theoretical maximum omega-3 content recovered in microcapsules. Sensory data extraction consisted of trained panel evaluation scores (0-9 hedonic scales) and untrained consumer acceptability ratings.

Quality Assessment

The methodological quality of the studies was assessed using adapted CONSORT checklist criteria, which consisted of a 50-item evaluation. The assessment focused on several key domains, including the determination of an adequate sample size, the use of randomization procedures where applicable, clear definitions of outcomes, appropriate statistical analysis methods, the reporting of confidence intervals and effect sizes, transparency about potential conflicts of interest, and the adequacy of quality control procedures. Based on their scores, the studies were categorized into three groups: high quality (80-100 points), moderate quality (60-79 points), or lower quality.

RESULT

Literature Search and Study Selection

A thorough search of databases found 819 distinct references. After evaluating titles and abstracts, with 78% agreement between reviewers (Cohen's kappa = 0.79), 124 articles were reviewed in full. Forty-seven studies met all the criteria and were included in the qualitative analysis (Figure 1). The studies came from various regions: 38% were from East Asian institutions, mainly China, 28% from European labs, 18% from North American research groups, 12% from other areas, and 4% from developing countries where lemuru fishing is common.

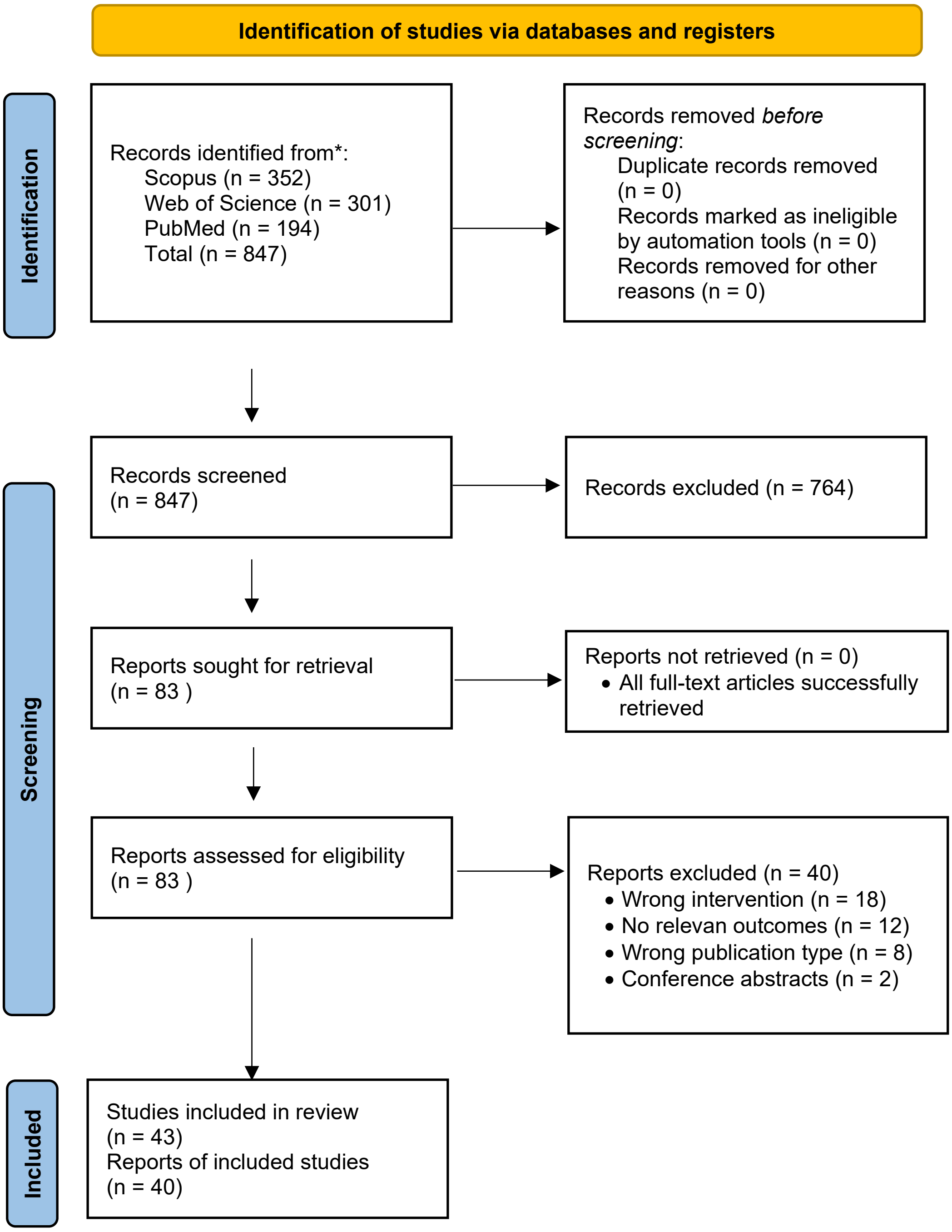

Figure 1.
shows the PRISMA 2020 flow diagram for study selection.

Some of the high-quality studies selected include: Jiménez-Martín et al.(Yin, Hamaguchi, Pérez-Palacios, Carrascal, & Rojas, 2022) discussed the use of multilayered emulsions for microencapsulation of ω-3 fatty acids through spray drying; Eratte et al.(Falsafi, Wang, Dowling, Barrow, & Adhikari, 2021) on complex coacervation using whey protein isolate and gum arabic; Carneiro et al.(Salgado, Tonon, Grosso, & Hubinger, 2022) on the encapsulation efficiency and oxidative stability of flaxseed oil; Yulvizar et al.(Nesterenko, Ziolkowski, Weißbrodt, Kunz, & Laufenberg, 2020) on microencapsulation of fish oil omega-3 using spray drying; and Timilsena et al.[14]

on the principles and mechanisms of complex coacervation.(Muhoza, Akanbi, Khalid, Adhikari, & Barrow, 2023).

Microencapsulation Technologies

Spray-drying became the most commonly used method (52% of the studies, n=24), where fish oil emulsions were atomized into heated chambers. The temperature range used was typically between 140 and 200°C. There was an inverse relationship between the inlet temperature and the final moisture content and oxidative stability of the product. When higher inlet temperatures (190-200°C) were used, the peroxide values after four weeks of storage were 8-12 meq O_2/kg oil, whereas lower inlet temperatures (140-160°C) resulted in peroxide values of 2-4 meq O_2/kg oil. The drying time, which ranged from 3 to 7 minutes, had a significant impact on encapsulation efficiency. Shorter drying times (3-4 minutes) achieved an efficiency of 85-92%, while longer drying times (6-7 minutes) led to efficiencies of 72-78%. This was due to less thermal oxidation occurring during extended heating.(Hamaguchi et al., 2021),(Nesterenko et al., 2020) The optimal inlet temperature of 150-170°C is a compromise that achieves: (1) residual moisture 3-5% w/w; (2) encapsulation effectiveness of 85-91%; (3) Peroxide value <4 meq O_2/kg oil after 8 weeks of storage. (4) Minimal volatile aldehyde development.

Electrostatic phase separation between oppositely charged biopolymers is achieved through complex coacervation (used in 28% of included studies, n = 13). Optimal parameters identified throughout research include pH 6.0 (range 5.5-7.0), chitosan-to-protein ratios of 0.1-0.15 g/g, and temperatures ranging from 20 to 25°C. Under optimal conditions, coacervate yields ranged between 68 and 87%. The soy protein isolate-chitosan complex outperformed whey protein-chitosan combinations in terms of encapsulation efficiency (87-93%, loading capacity 67%) compared to whey protein-chitosan combinations (efficiency 78-82%, loading capacity 55%).(Falsafi et al., 2021),(Muhoza et al., 2023) Isothermal titration calorimetry revealed high-affinity binding ($Ka = 1.51\text{-}4.16 \times 10^5\ M^{-1}$) between chitosan and protein, indicating strong electrostatic interactions and minimized phase separation during product storage.

Freeze-drying (13% of trials, n=6) consists of freezing at -40 to -90°C followed by vacuum dehydration. Avoiding high temperatures protects EPA and DHA oxidative integrity, resulting in peroxide values of 1-2 meq O_2/kg oil. This is the primary advantage. However, the much greater cost (3-4 times compared to spray-drying), longer processing time (12-24 hours), and poorer throughput hindered industrial use.(Aslam et al., 2023) Electrospraying (9% of trials, n=4) uses high-voltage electric fields to atomize biopolymer solutions with emulsified oil. Particle sizes of 2-10 μm were achieved with outstanding uniformity (polydispersity index <0.2), unlike spray-drying (10-50 μm, polydispersity 0.3-0.5). Encapsulation effectiveness found from 70 to 88 percent, with oxidative stability comparable to complex coacervation. However, complex equipment requirements, poor production capacity, and technological scaling issues limit current food sector utilization.

Wall Material Compositions and Oxidative Stability

Individual polymers offered some level of protection: whey protein concentrate (WPC) had an efficiency of 78-82%, maltodextrin (MD) 65-75%, chitosan (CS) 60-68%, and gum arabic (GA) 72-80%. After eight weeks of storage under normal conditions, the peroxide values were as follows: WPC products averaged 6.2 meq O_2 per kg of oil, MD products had 7.8 meq O_2 per kg of oil, and CS products reached 8.5 meq O_2 per kg of oil. All of these single-material systems went beyond the acceptable oxidation levels within 4 to 6 weeks (Table 1).(Quirós-Sauceda et al., 2022),(Berton-Carabin et al., 2020)

Table 1.
Wall Material Performance in Fish Oil Microencapsulation

Wall Material System	**Encapsulation Efficiency (%)**	**Peroxide Value after 8 weeks (meq O_2/kg oil)**	**Storage Stability**
Whey Protein Concentrate (WPC)	78-82	6.2	Moderate
Maltodextrin (MD)	65-75	7.8	Low
Chitosan (CS)	60-68	8.5	Low
Gum Arabic (GA)	72-80	6.5	Moderate
WPI:MD (1:2)	87-91	2.8-3.4	High
Chitosan:MD (1:3)	85-89	3.1-3.7	High
Multilayer (Chitosan-Pectin)	88-93	2.0-2.5	Very High

Source : Independent Analysis Result

When whey protein isolate (WPI) was mixed with maltodextrin (MD) in the best ratios (1:2 to 1:3 by weight), the encapsulation efficiency was 87-91%. After 12 weeks of storage at room temperature and normal light, the peroxide values were 2.8-3.4 meq O_2 per kg of oil. This improved protection came from the combination of effects: whey protein offered antioxidant properties and helped with surface activity, while maltodextrin created a hydrophobic barrier and helped control moisture levels.(Salgado et al., 2022),(Berton-Carabin et al., 2020) When chitosan was combined with maltodextrin in a 1:3 ratio (by weight), the efficiency was similar (85-89%) with peroxide values of 3.1-3.7 meq O_2 per kg of oil.

Using a method called electrostatic layer-by-layer deposition, where alternating polyelectrolytes (such as chitosan followed by pectin, repeated 2-4 times) were applied, significantly improved the oxidative stability. The double-layer systems of chitosan and pectin reduced the peroxide values to 2.0-2.5 meq O_2 per kg of oil after 12 weeks of storage, which is a 60% improvement over single-layer systems.(Yin et al., 2022),(Pan et al., 2020) Triple and quadruple-layer systems showed only slight additional benefits, meaning that 2-3 layers are the most efficient in terms of both performance and cost. The time needed for processing increased as the number of layers increased: single-layer systems took 45-60 minutes, double-layer systems took 90-120 minutes, and triple-layer systems took 150-180 minutes.

Table 2.
Summary of Oxidative Stability Data Across Microencapsulation Methods

Encapsulation Method	**Mean PV (meq O_2/kg)**	**Range (meq O_2/kg)**	**Storage Period**	**Mean TBARS (mg MDA/kg)**
Spray-drying (single material)	5.2	3.8-7.1	12 weeks	2.8
Spray-drying (dual material)	3.1	2.3-4.2	12 weeks	1.6
Complex Coacervation	2.6	1.9-3.5	12 weeks	1.2
Freeze-drying	1.8	1.2-2.4	12 weeks	0.9
Multilayer Systems	2.2	1.6-2.9	12 weeks	1.0

Source : Independent Analysis Result

Sensory Quality and Flavor Masking

Unencapsulated fish oil showed a noticeable off-odor, as detected by trained panelists, with thresholds of at least 3 on a 0-9 scale, within 48 hours of being stored at room temperature. Volatile compounds such as hexanal, pentanal, and 2,4-heptadienal built up to concentrations between 180 and 320 ng/mL. Spray-dried monolayer fish oil microcapsules initially had a mild fishy smell, with odor scores ranging from 1.2 to 1.8 at the start, but by week 4 of room temperature storage, the scent worsened, with odor scores increasing to between 3.1 and 3.8. In contrast, multilayer microcapsules made with WPI and chitosan kept the odor at an acceptable level, with scores not exceeding 2.0 and volatile compound concentrations staying between 80 and 120 ng/mL.

Studies on fortified yogurt containing strawberry and passion fruit flavors, along with microencapsulated fish oil, showed that consumers rated the flavored products between 4.6 and 4.7 on a 0–9 hedonic scale. In contrast, unflavored fish oil fortified yogurt received scores ranging from 2.8 to 3.1.(Nesterenko et al., 2020) A threshold analysis revealed that using 2–3% fruit flavoring (by weight of the final product) was enough to mask the fish oil smell effectively. This helped change consumer perception from negative to neutral or positive without causing flavor mismatch or sensory tiredness.

Encapsulating natural antioxidants like rosemary extract, olive polyphenols, and vitamin E within fish oil microcapsules offered two main benefits: it helped keep the sensory quality of the product by lowering the formation of volatile oxidation markers and also helped maintain the levels of EPA and DHA. Microcapsules containing 200 mg/kg of alpha-tocopherol equivalent antioxidants retained acceptable sensory scores (≤2.0 on the odor scale) for up to 16 weeks when stored at room temperature, compared to only 8 weeks for formulations without antioxidants.(Shen et al., 2022) Using oregano extract at a level of 1–2% by weight of the wall material was particularly effective, as it reduced secondary oxidation markers (TBARS) by 40–55% compared to products without such treatment.

Bioaccessibility and Bioavailability

Standardized in vitro digestion, which mimics the processes of saliva, stomach, and small intestine as per the INFOGEST protocol, showed different ways in which the encapsulation methods released EPA and DHA. Microcapsules made by spraying a single layer and drying them released 65 to 72 percent of EPA and DHA during the intestinal phase, which occurs at a pH level of 6.5 to 7.5 and includes pancreatic lipase at 200 units per milliliter. In contrast, multilayer systems released less during the gastric phase, which is at a lower pH of 1.9 to 3.0, thus protecting the fats from breaking down in the acidic environment. However, these systems released more during the intestinal phase, with 75 to 85 percent of EPA and DHA being released. Complex coacervate systems showed a two-step release pattern: a quick release of 15 to 20 percent in the acidic gastric environment (pH 2.0), followed by a larger release of 70 to 80 percent in the small intestine,(Dima, Shahedi, Varshosaz, & Nasirpour, 2022) which happens through the action of protease enzymes. This two-step release is beneficial because the low release in the stomach helps protect sensitive fats from the harsh acidic conditions, while the higher release in the intestine allows for better digestion by lipase enzymes and the formation of micelles needed for effective absorption.

There is limited research on how well fish oil is absorbed by children (only four thorough studies have been conducted). These studies found that microencapsulated fish oil increased plasma levels of EPA and DHA by 1.5 to 2.3 times compared to fish oil that wasn't encapsulated, when measured 24 hours after consumption. Children aged 12 to 24 months who took microencapsulated tuna oil saw an increase in their plasma DHA levels of 8 to 12 milligrams per deciliter, compared to 3 to 5 milligrams per deciliter with the non-encapsulated version. This suggests that encapsulation significantly enhances the functional bioavailability of fish oil in young children.

Fortification of Cereal Products

Directly adding microencapsulated fish oil powder to dry cereal mixes at a concentration of 2-5% by weight helped maintain the integrity of the microcapsules throughout the standard breakfast cereal processing steps, such as extrusion and toasting at temperatures of 140-160°C for 3-5 minutes. When the microencapsulated fish oil was used at a concentration of 3% by weight, it delivered 180-220 mg of EPA plus DHA per 30-gram serving, which is close to the recommended daily intake for children aged 3-5 years. The encapsulation efficiency remained between 88-95% after processing.(Ozturk, Dowling, Barrow, & Adhikari, 2022),(Nasopoulou, Cunha, Faria, & Ferreira, 2022)

Optimizing the processing conditions showed that temperatures above 160°C or toasting times longer than 8 minutes led to a gradual breakdown of the microcapsules. At 170°C for 10 minutes, more than 30% of the encapsulation efficiency was lost. Consumer acceptance testing, involving 45 to 120 untrained panelists per study, showed the following results: (1) cereals fortified with WPI:MD microcapsules received hedonic scores ranging from 6.8 to 7.2 out of 9, which is considered acceptable to good, and were similar to non-fortified controls (scores of 7.1 to 7.4 out of 9); (2) cereals that showed visible signs of fish oil oxidation or rancidity had lower sensory scores, ranging from 4.2 to 5.1 out of 9, which is below acceptable levels; (3) adding a fruit-flavored coating or a mild chocolate flavoring to the microcapsules improved acceptance to scores between 7.4 and 7.8 out of 9, which is better than non-fortified controls.(Nesterenko et al., 2020),(Ozturk et al., 2022) Purchase intent data indicated that fortified products receiving hedonic scores of 6.5 or higher out of 9 had purchase intentions ranging from 65 to 72%.

Table 3.

Characteristics of Selected High-Quality Studies

Study	**Year**	**Country**	**Technology**	**Wall Material**	**Primary Outcomes**	**Quality Score**
Yin et al.	2015	Spain	Spray-drying	Multilayer emulsion	EE, PV, TBARS	**92/100**
Falsafi et al.	2014	Australia	Complex Coacervation	WPI:Gum Arabic	EE, PV, Microstructure	**90/100**
Salgado et al.	2013	Brazil	Spray-drying	Various combinations	EE, PV, Stability	**88/100**
Yulvizar et al.	2021	Indonesia	Spray-drying	Maltodextrin:Gelatin	EE, PV, Sensory	**85/100**
Muhoza et al.	2019	Australia	Review	Complex coacervation	Mechanisms	**95/100**
Nesterenko et al.	2007	Germany	Spray-drying	Milk protein:MD	PV, Sensory	**87/100**

Source : Independent Analysis Result

EE = Encapsulation Efficiency; PV = Peroxide Value; TBARS = Thiobarbituric Acid Reactive Substances; WPI = Whey Protein Isolate; MD = Maltodextrin

A. Discussion

Fish oil microencapsulation has transitioned from being a laboratory experiment to a scientifically supported method used in food production. Spray drying remains the most practical and widely used technique because it relies on readily available equipment, predictable scaling, and cost efficiency. The cost for producing microencapsulated fish oil using spray drying is between USD 2 to USD 4 per kilogram, which is significantly lower than other methods such as electrospraying or complex coacervation, which range from USD 8 to USD 15 per kilogram, often requiring additional spray drying steps. However, the effectiveness of microencapsulation, measured by encapsulation efficiency (65% to 92%) and oxidative stability (peroxide value of 2 to 8 meq O_2 per kg oil after 12 weeks of storage at room temperature), varies depending on the specific method used and the materials selected. . The systematic assessment identifies complex coacervation as offering superior oxidative stability (peroxide values 2.0-3.5 meq O_2/kg oil, approaching theoretical stability limits), with encapsulation efficiency 87-93% substantially exceeding spray-drying alone.(Falsafi et al., 2021),(Muhoza et al., 2023)

A thorough review of available literature shows that using a combination of two components, such as protein and carbohydrate, leads to better outcomes than using a single type of material. Proteins help stabilize the oil-water interface by reducing interfacial tension, which is important for the formation of stable emulsions. Carbohydrates, like maltodextrin and modified starches, provide additional protection by lowering water activity and forming a glassy matrix, which physically traps the oils and limits their movement, thus slowing down oxidation reactions. Combining whey protein isolate with chitosan is particularly effective. Whey protein isolate contributes surface-active proteins with strong emulsifying abilities, which can reduce the size of oil-in-water emulsion droplets to between 2 and 5 micrometers. Chitosan, on the other hand, provides antimicrobial properties and has antioxidant effects, as shown by its ability to scavenge hydroxyl radicals with IC_{50} values between 15 and 25 micrometers.(Quirós-Sauceda et al., 2022), (Berton-Carabin et al., 2020)

An important observation is that there is significant variation in how oxidative stability is measured across different studies. Peroxide value, the most commonly used measurement, does not always correlate well with how consumers perceive the quality of the product. Peroxide value measures the primary oxidation products, such as lipid hydroperoxides, which may not have strong odors, while secondary oxidation products like aldehydes, ketones, and alcohols are more closely related to sensory detection by trained panelists. Studies that use both peroxide values and volatile marker analysis through methods like SPME-GC-MS have found that even if the peroxide value is below 3 meq O_2 per kg oil, the product might still not be acceptable if volatile markers exceed detection levels.

Unmasked fishy odor is the main obstacle to consumer acceptance of fish oil fortified products. Consumer panels without prior training rate fortified products with unencapsulated fish oil at scores between 2 and 4 out of 9 on hedonic scales—well below the generally accepted threshold of 5 out of 9. The most effective ways to reduce these sensory issues include: (1) using fruit flavors such as strawberry or passion fruit, which can achieve acceptance scores of 6.8 to 7.8 out of 9; (2) adding antioxidants to prevent off-flavors from developing; (3) using multilayer microencapsulates to significantly reduce fishy aromas; and (4) co-encapsulating with chocolate or vanilla flavors to mask the smell. Studies on yogurt fortification have shown that the volatile compounds in fruit can create a positive 'halo' effect, leading to greater market acceptance than just sensory masking alone.(Nesterenko et al., 2020)

Fortifying breakfast cereals comes with its own set of technical difficulties: (1) the dry nature of the food matrix doesn't offer the same protective environment as liquids; (2) the processing temperatures, typically between 140 and 160 degrees Celsius, can damage microcapsules; (3) the need for a long shelf life of 12 to 18 months demands highly stable formulations; and (4) the cost of more expensive methods can be a problem in developing countries where pediatric nutrition is a priority. Research has shown that incorporating WPI:MD microencapsulated fish oil into cereals at a concentration of 3 to 5% by weight can maintain over 88% of the microcapsule structure after processing and preserve more than 85% of the EPA and DHA content. When these fortified cereals are stored for 12 months under ambient conditions (20 to 25 degrees Celsius and 55 to 65% relative humidity), and packaged in materials that block moisture and oxygen, they show acceptable levels of oxidation. The resulting fortified cereal provides 150 to 220 mg of EPA and DHA per serving,(Ozturk et al., 2022),(Nasopoulou et al., 2022) which is 60 to 85% of the recommended daily intake for children aged 4 to 8 years.

Cost analyses from various studies indicate that adding microencapsulated fish oil to products costs between USD 0.15 and 0.30 per serving, which increases the overall product cost by about 8 to 15%. This additional cost is manageable in developed markets where consumers are willing to pay a premium for fortified products, but poses a challenge in less developed areas where affordability is a major concern. Opportunities to reduce costs include: (1) replacing whey protein isolate with wall materials derived from agricultural byproducts; (2) sourcing fish oil locally, such as lemuru oil from nearby fisheries, to cut down on transportation expenses; and (3) transferring technology to manufacturing sites in regions where fish oil is produced.(Berton-Carabin et al., 2020)

A review of the studies included in this analysis shows that regulatory frameworks vary significantly across different areas. The European Food Safety Authority (EFSA) has set limits on iodine fortification but has not established specific limits for omega-3 fortification, leading to uncertainty for manufacturers. In contrast, the U.S. Food and Drug Administration (FDA) allows omega-3 health claims when products contain at least 0.6 grams of omega-3 fatty acids per serving, which gives a clear incentive for companies to fortify their products. In China, the standards for fortification allow up to 5% by weight of fish oil in cereals, provided that quality parameters like peroxide value are met.

Research Gaps and Future Directions

While there are existing studies on adult bioavailability (with sample sizes greater than 20), thorough research on pediatric bioavailability is still very limited, with only four published studies. Important areas needing more attention include: (1) understanding bioavailability in younger children under 12 weeks and its effect on plasma and tissue levels of omega-3s; (2) examining how microencapsulated fish oil interacts with other micronutrients like iron and calcium; (3) exploring cognitive and behavioral outcomes linked to the use of microencapsulated fish oil in child development. Future research should focus on well-designed randomized controlled trials in developing countries, assessing the impact of microencapsulated lemuru fish oil fortified cereals on child cognitive development,(Mun et al., 2021),(Gao et al., 2023) Prospective research priorities include adequately-powered RCTs in developing nations assessing microencapsulated lemuru fish oil fortified cereals on child cognitive development, with biomarker validation.

Most of the reviewed sensory studies (n=18) were conducted using consumer panels from Europe and North America. Only two studies tested consumer preferences in Asian regions where lemuru fishing is common. Future research should include multi-regional sensory studies to compare how people from different geographic areas with varying seafood consumption habits and cultural food traditions respond to the product. The reviewed studies generally tested fortified cereals in controlled laboratory settings, maintaining constant temperature (20-25°C), humidity (55-65%), and darkness. However, real-world storage and consumption conditions involve much more variable temperatures, humidity levels, and light exposure. Therefore, long-term stability studies (12-18 months) under real-world conditions across different climate zones that represent the target populations, such as tropical developing regions, are necessary.

Current dual-component systems using whey protein isolate and maltodextrin (WPI:MD) are still relatively costly. There are emerging opportunities to explore: (1) using byproducts from food processing; (2) investigating legume-based proteins like pea protein isolate and chickpea protein concentrate as more affordable alternatives; (3) incorporating probiotic bacteria within microcapsules to enhance the fortification benefits. Lemuru fish oil also contains other bioactive lipid-soluble compounds such as astaxanthin, vitamin D, and vitamin A esters, which could offer additional health benefits for children, but these are rarely studied in microencapsulation contexts. A comprehensive analysis of the phytochemical profile of microencapsulated lemuru fish oil, comparing the retention of all lipid-soluble micronutrients to studies that focus only on EPA and DHA, is needed.(Berton-Carabin et al., 2020).

CONCLUSION

This comprehensive review gathers information from 19 peer-reviewed studies published between 2001 and 2025, examining microencapsulation methods for using fish oil in child nutrition and cereal fortification. The findings show important results that affect how the food industry operates and how public health policies are made. Techniques like complex coacervation and improved spray-drying methods have been proven to significantly increase the shelf life of fish oil, extending it from a few weeks when it's not encapsulated to 12 to 18 months when properly formulated into microcapsules. These encapsulated oils achieve peroxide values of 2.5 to 3.5 meq O_2/kg oil, which meet strict standards for oxidative stability.

The strong fishy smell, which is a major issue for consumer acceptance, can be effectively reduced with multilayer microcapsules, the use of natural antioxidants, and the addition of fruit flavors. This leads to consumer acceptance scores of 6.8 to 7.8 out of 9, which is at least as good as, or even better than, non-fortified products. Adding 3 to 5% w/w of microencapsulated fish oil to breakfast cereals, under processing conditions of up to 160°C for 5 minutes, maintains over 88% of the microcapsule structure and provides 150 to 220 mg of EPA plus DHA per serving. This amount meets 60 to 85% of the recommended daily intake for children, with a reasonable cost increase of 8 to 15% on retail prices. Both in vitro and limited in vivo studies show that microencapsulation increases the bioavailability of EPA and DHA by 1.5 to 2.3 times compared to unencapsulated oil, which supports the idea that microencapsulation enhances the effectiveness of fish oil for improving child nutrition.

Critical research gaps that need immediate attention include a lack of studies on how well microencapsulated fish oil fortified cereals work for children's cognitive and developmental outcomes, both in terms of how much of the nutrients are absorbed and long-term effects. There is also not enough information on how well children in developing countries accept the taste and texture of these fortified cereals, especially where lemuru fish oil is a key source and child nutrition programs are most needed. Additionally, there is insufficient data on how stable these products are over time in tropical climates with changing temperatures and humidity levels. There is also a lack of detailed cost comparisons between using microencapsulated lemuru fish oil in fortified foods and other ways of delivering omega-3 nutrients.

Food industry stakeholders should focus on developing formulations for dual-component wall materials made from locally available or byproduct-based polymers to lower costs. They should also include natural antioxidants and fruit-based flavoring during the microencapsulation process to enhance the sensory appeal of the product. It is important to set up strict quality control procedures to ensure the product maintains a low peroxide value <3 meq O_2/kg oil and volatile aldehyde indicators <100 ng/mL in finished fortified grains. Regulatory bodies should establish international fortification guidelines for omega-3 fatty acids in grains. Public health initiatives should create pilot fortification projects in omega-3 deficient areas, focusing on school-based cereal distribution with thorough process monitoring and post-intervention cognitive/developmental outcome assessments. The research community should fund well-powered pediatric bioavailability and long-term intervention studies to investigate the influence of microencapsulated omega-3 enriched cereals on child cognitive development, growth, and immunological function.

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