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Trends and viability of omega-3 fatty acid microencapsulation: A bibliometric and critical analysis

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ABSTRACT

This study combines a bibliometrics analysis and a critical review on the microencapsulation of omega-3 fatty acids derived from animal, plant, and protist sources, aiming to identify scientific trends, advances in oxidative stability, and the physicochemical mechanisms responsible for lipid protection. Research published between 2010 and 2024 in the Scopus, Web of Science, and PubMed databases was examined, selecting 92 studies that met the inclusion criteria. The bibliometric analysis revealed a sustained increase in scientific production, with China, Unites States, and Argentina identified as the leading contributors, and Food Chemistry as the most influential journal in the field. The results demonstrate that microencapsulation processes significantly improve oxidative stability and extend the shelf life of omega-3 fatty acids for up to three months under controlled storage conditions. The most employed techniques were spray drying, complex coacervation, lyophilization, and coaxial electrospraying, all showing the ability to from dense structures with acceptable encapsulation efficiency (>60%) and low zeta potential (approximately -50 mV). The wall materials with the best rheological performance were polysaccharides (maltodextrin, chitosan, gum Arabic) and proteins (zein, whey isolate, and caseinate), which act through electrostatic and hydrophobic interactions that strengthen the protective matrix. The protective effect is attributed to the formation of semipermeable barriers that limit oxygen diffusion and free radical propagation, thereby preserving the profile of essential fatty acids (ALA, EPA, and DHA). These findings reinforce that microencapsulation is an effective strategy for maintaining fatty acid integrity and developing functional foods enriched with omega-3s.

1. Introduction

In recent decades, growing awareness of the relationship between diet and health has driven significant interest in functional foods, particularly those enriched with vitamins (Espinoza-Espinoza et al., 2024), minerals (Nole-Jaramillo et al., 2024), and omega-3 fatty acids (Nazzaro et al., 2024). Fatty acids are essential components of the human diet, playing key roles in maintaining and regulating vital physiological functions. Among them, omega-3 fatty acids have gained particular relevance due to their well-documented benefits on cardiovascular health, neurological development, and reduction of inflammatory processes, as well as their potential role in preventing certain types of cancer, such as breast and prostate cancer (Dia et al., 2024). These bioactive compounds have become fundamental elements in the development of foods with health-promoting properties (Gómez-Fernández et al., 2021; Ruiz Ruiz et al., 2017). Among the main natural sources of omega-3, vegetable oils stand out for their high α-linolenic acid content, which has been associated with positive effects on lipid metabolism and cardiovascular health (Dabiri Movahed et al., 2024). In general, oils are characterized as rich matrices of polyunsaturated fatty acids, antioxidants, and polyphenols compounds linked to antihypertensive, anticancer, and cholesterol-lowering

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properties (Rezvankhah & Emam, 2018).

Despite the high functional potential of omega-3 fatty acids, their incorporation into food matrices remains challenging, as they are highly susceptible to oxidation and alterations in their organoleptic properties (Ghorbanzade et al., 2017; Rengifo et al., 2024; Siripongvutikorn et al., 2016). These challenges require a multidisciplinary approach through innovative technologies to stabilize and effectively deliver omega-3 in functional foods (Prieto & Lagaron, 2020; Sandhya et al., 2023).

The evolution of this field shows significant advances in encapsulation techniques, from conventional microencapsulation to advanced nanotechnology applications (Keshri et al., 2024; Yang et al., 2024). Concurrently, the development of new encapsulation materials, optimization of production processes, and evaluation of the stability and bioavailability of bioactive compounds have been areas of intense research (Engelmann et al., 2024; Shakeri et al., 2024).

In recent years, several high-impact narrative reviews have been published on omega-3 stabilization, addressing protein-based emulsions and spray drying (Chang & Nickerson, 2018), colloid technologies from marine sources (Venugopalan et al., 2021), extrusion-dripping and co-encapsulation techniques (Sultana et al., 2022), the role of biopolymers and antioxidants in physical oxidative stability (Du et al., 2022), and *in vivo* bioavailability (Homroy et al., 2023). However, these studies lack a bibliometric approach capable of quantitatively mapping the historical evolution of research, identifying emerging trends through thematic clustering, and objectively correlating influential contributors with effective technical clustering, and objectively correlating influential contributors with effective technical methodologies. Therefore, conducting a comprehensive bibliometric and systematic analysis becomes essential to understand current research trends, identify key contributors, examine the geographic distribution and international collaboration networks, and assess the field's evolution complemented by a critical review of experimental studies to highlight the encapsulation technologies applied in the development of omega-3 enriched functional foods (Donthu et al., 2021).

The critical review of experimental studies focuses on omega-3 sources (animal, plant, and protist), evaluating the influence of various encapsulation techniques on the efficiency, oxidative stability, and bioavailability of omega-3 fatty acids. The integration of these approaches allows projecting new directions for research, fostering technological innovations that improve the incorporation of omega-3 in functional food products, allowing highlighting opportunities to refine current processes that promote the sustainable development of functional foods with high added value.

2. Methodology

This study is based on a mixed-methods approach that integrates bibliometric analysis and a critical review of experimental studies on the microencapsulation of omega-3 fatty acids. The combination of both perspectives allows for a comprehensive approach to the state of research, identifying not only the dynamics of scientific production and global collaboration but also the experimental advancements in encapsulation processes, their effects on efficiency, oxidative stability, and the bioavailability of these bioactive compounds.

2.1. Search strategy and data collection

The initial phase consisted of a comprehensive search for scientific publications in the Scopus, Web of Science and Pubmed, database, recognized for its broad coverage and quality in the academic field (Pant et al., 2021; Pranckutė, 2021). The following search equation was used to identify relevant articles:

TITLE-ABS-KEY ((("functional food*" OR "fortified food*" OR "enriched food*") AND ("omega-3" OR "omega 3" OR "n-3 fatty acid*" OR "polyunsaturated fatty acid*" OR "PUFA" OR "EPA" OR "DHA") AND ("encapsulation" OR "microencapsulation" OR "nanoencapsulation" OR "nanotechnology" OR "nanoparticle*" OR "nanoemulsion*" OR "non-thermal processing" OR "high pressure processing" OR "pulsed electric field*" OR "ultraviolet" OR "emerging technology*") AND ("stability" OR "oxidation" OR "shelf life" OR "sensory evaluation" OR "quality assessment" OR "storage stability")))

The search was restricted to publications between 2010 and 2024 in order to cover both pioneering studies and the most recent and relevant research in the field. To ensure the relevance and specificity of the analysis, only scientific articles published in English, categorized as "journal" sources, and in their final publication stage were included. Reviews, book chapters, conference proceedings, and articles not directly related to the encapsulation of omega-3 in functional foods were excluded.

2.2. Data preparation

The results obtained from the bibliographic search were exported in CSV format and processed using OpenRefine (v3.9.2) to remove duplicates and correct inconsistencies in the metadata (Ahmi, 2023; Miller & Vielfaure, 2022). In the experimental review, the data were organized into comparative tables, allowing for a clear view of the differences between techniques and matrices used. Each category in the table highlights the technical, chemical, and functional aspects of the microcapsules, enabling a critical evaluation of their performance and potential applications.

2.3. Bibliometric analysis

The bibliometric analysis was conducted through the synergistic implementation of two specialized software tools: VOSviewer (v1.6.18) and Bibliometrix (v3.1.4 for R). VOSviewer was used for visualizing bibliometric networks and analyzing keyword co-occurrence, facilitating the identification of collaboration patterns and thematic trends (Perianes-Rodriguez et al., 2016). At the same time, Bibliometrix was used for advanced statistical analysis and the generation of comprehensive bibliometric indicators, allowing for a robust quantitative characterization of the research corpus (Aria & Cuccurullo, 2017). This dual methodological approach enabled a multidimensional and rigorous analysis of scientific literature in the field of omega-3-enriched functional foods.

The following key aspects were evaluated:

- Temporal evolution of scientific production: The annual distribution of publications was analyzed to identify productivity peaks and emerging trends.
- Geographic distribution and collaboration networks: The main research centers and their international collaborations were mapped, identifying the most active clusters.
- Influential journals and authors: The publications and authors with the greatest impact on knowledge dissemination were determined, based on the number of published articles and citations received.
- Thematic structure of the field: Through keyword co-occurrence, the predominant and emerging research areas were identified, allowing for the mapping of the intellectual evolution of the field.

2.4. Critical review of experimental studies

In parallel with the bibliometric analysis, a critical review of experimental studies focused on the micro and nanoencapsulation of omega-3 was conducted. This phase provided insights into technological advancements, identifying the most effective techniques to improve encapsulation efficiency, oxidative stability, and bioavailability of omega-3 fatty acids. The reviewed studies were organized into three categories based on their source of origin: plant, animal, and protist.

Each study was evaluated based on the following parameters:

- Core or source of encapsulation: The sources of omega-3 were detailed.
- Encapsulation technique: Methods such as spray drying, emulsification, Freeze drying, complex coacervation, microfluidization, etc., were documented.
- Size and morphology: The physical characteristics of the capsules were analyzed to determine their structural stability.
- Encapsulation efficiency (EE): The ability of the capsules to retain the compound during the encapsulation process was evaluated.
- Oxidative stability: The effects of encapsulation techniques on protecting omega-3 fatty acids from oxidation were examined.
- Fatty acid profile: The preservation of the lipid profile during the encapsulation process was analyzed.

3. Results and discussion

3.1. Bibliometric analysis

3.1.1. Temporal evolution of publications

The bibliometric analysis of manuscripts focused on the microencapsulation of omega-3 fatty acids between 2010 and 2024 reveals a growing field of research, with an annual growth rate of 17.35%. This evolution is characterized by two distinct phases: an initial phase from 2010 to 2014, marked by variable and exploration production with 14 publications, followed by a growth phase from 2015 to 2024, totaling 96 publications (Fig. 1). This pattern aligns with Rogers' innovation diffusion model, reflecting the field's transition from pioneering efforts to greater acceptance and maturity (Albertsen et al., 2020).

The observed trajectory suggests that research on omega-3-enriched functional foods has been attracting increasing attention. The productivity peaks in 2021 and 2022, as well as the recent stabilization at 10 annual publications, indicate sustained interest and potential for future growth (Hyatt et al., 2023; Khan et al., 2023). This development is framed within a broader context of growing interest in personalized nutrition and functional foods, positioning this research field at the intersection of important trends in food science, nutrition, and public health (Patel et al., 2022).

3.1.2. Geographic distribution of research

The analysis of the geographic distribution of research on omega-3-enriched functional foods reveals a diverse and dynamic global landscape. China leads with 82 authors, followed by Argentina with 58, while countries such as Iran, Spain, India, and the United States form a second significant group with between 30 and 35 authors (Fig. 2). This distribution reflects a complex interplay of economic, political, and scientific factors. China's leadership can be attributed to its substantial investment in I+D, national policies prioritizing innovation, and an expanding domestic market (Giang, 2020). Argentina's notable production is explained by its abundance of natural resources rich in omega-3 (Cretton et al., 2020; Dellatorre et al., 2020; Pascual-Silva et al., 2022; Sosa et al., 2020) and international collaborations (Belli & Morín Nenoff, 2022).

The observed geographic diversity, which includes both emerging economies and developed countries, suggests a democratization of scientific knowledge in this field. This phenomenon aligns with the growing multipolarity of global science and reflects a "technological catch-up" where developing countries invest in emerging research areas (Camacho Toro et al., 2024; Vieira et al., 2022).

3.1.3. Most influential journals

In the field of omega-3 fatty acid microencapsulation, *Food Chemistry* stands out as the most influential journal. With 6.85% of documents accumulating 835 citations, it achieves an impressive citation rate of 167 citations per document. This high citation rate highlights the quality and relevance of the research published in this journal, which is distinguished by its focus on antioxidant compounds in food (Kamdem et al., 2019) (Fig. 3).

Other important journals show different patterns of impact and productivity. The *Journal of the Science of Food and Agriculture*, with 6.85% of documents and 50 citations, contrasts with *Food Research International* and *Journal of Food Engineering*, which account for 5.48% of documents and citations ranging from 300 to 254, respectively, demonstrating a balance between quantity and impact. Finally, *Food and Function* stands out for its high efficiency, encompassing 4.11% of manuscripts with 232 citations. The variation in citation numbers across journals suggests different levels of specialization and scope, with some publications standing out for their broad impact and others for their more specific focus (Zhang et al., 2021).

3.1.4. Most prolific authors

The analysis of the most prolific authors in the field of omega-3 fatty acid microencapsulation reveals lofty standards of scientific production. Notably and consistently, leading researchers stand out for their contributions of high-impact scientific work, with up to three publications per author on the topic of omega-3 fatty acid microencapsulation.

However, the true differentiation among these researchers is reflected in the number of citations received. This phenomenon aligns with Lotka's law in bibliometrics, which posits that a small proportion of authors in a field produce a large proportion of high-impact publications (Kretschmer & Kretschmer, 2007). In this context, Jafari stands out as a clear leader, with 555 citations, nearly doubling the impact of his closest colleagues. This level of citation can be attributed to the fact that Jafari's contributions have been particularly innovative or have addressed fundamental issues in the field, establishing new methodologies.

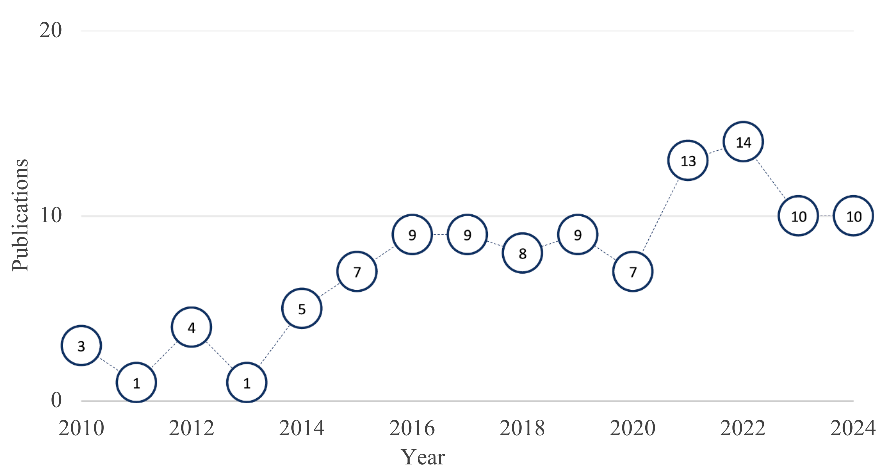

Fig. 1. Temporal evolution of publications focused on the microencapsulation of omega-3 fatty acids in Scopus.

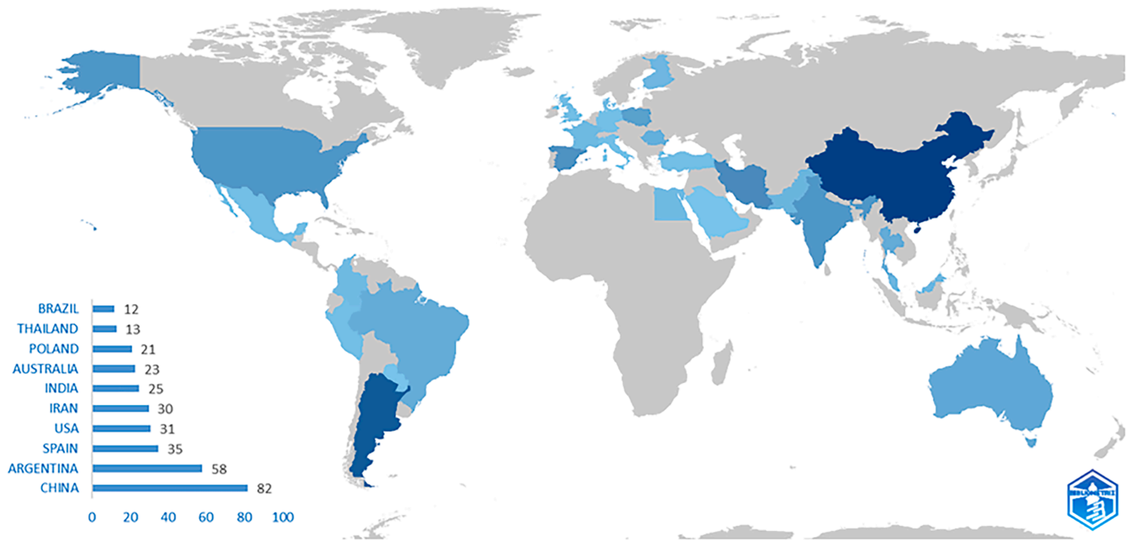

Fig. 2. Geographic distribution of publications focused on the microencapsulation of omega-3 fatty acids in Scopus.

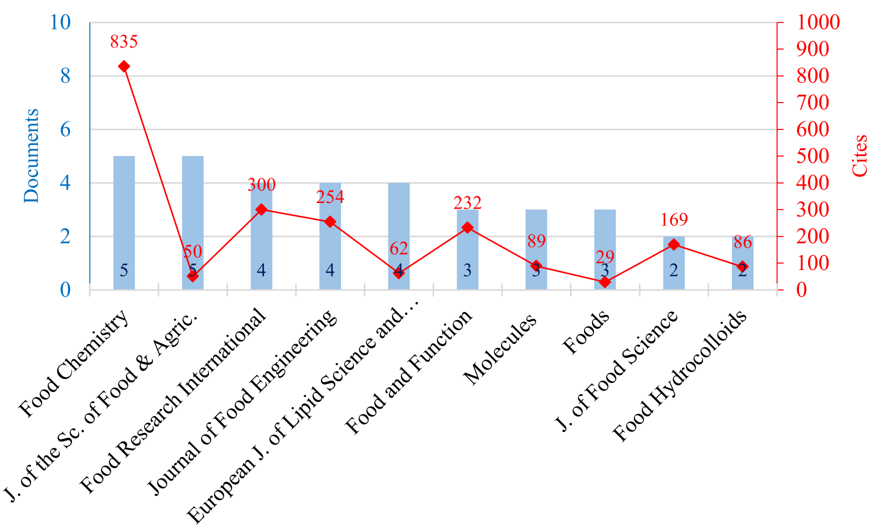

Fig. 3. Most influential scientific journals in publications focused on the microencapsulation of omega-3 fatty acids.

The distribution of citations among the other authors reveals a hierarchical structure in terms of scientific influence. Benu and Barrow, with 359 citations each, form a second level of influence, followed by McClements and Lagaron with over 200 citations. This stratification could reflect different approaches or areas of specialization within the field, each with its own level of relevance to the scientific community at large. On the other hand, the group formed by Marsanasco, Chiaramoni, and Alonso Silvia, who have the same number of citations (Fig. 4), is particularly interesting. This exact match in citation numbers strongly suggests close collaboration, forming a research team working on a specific aspect of the field.

The wide variation in the number of citations, ranging from 29 to 555, reflects the diversity and complexity inherent in this field of research. This dispersion can be interpreted through Rogers' theory of the diffusion of innovations. The highly cited works represent fundamental innovations that have been widely adopted by the scientific community, while the less-cited works reflect more recent contributions or ideas that are still in the early stages of diffusion and adoption (Aizstrauta et al., 2015).

3.1.5. Co-citation and co-occurrence keyword analysis

The keyword analysis in the microencapsulation of omega-3 fatty acids reveals a diverse and dynamic research landscape. "Omega 3" stands out as the central term, reflecting its fundamental role in this area of study. The high prominence of "oxidative stability" highlights one of the most critical challenges in the development of these functional foods: maintaining the integrity of omega-3 fatty acids against their susceptibility to degradation (Delfanian et al., 2023; Du et al., 2022; Yenipazar & Şahin-Yeşilçubuk, 2023).

Subsequently, terms related to encapsulation techniques, both at the micro and nano scales, appear as key approaches to addressing the challenges of stability and bioavailability (Chasquibol et al., 2023; Gimenez et al., 2023; Prieto & Lagaron, 2020; Shehzad et al., 2021). This trend is further supported by the presence of terms such as "nano-emulsion" and "spray drying," indicating a shift toward more advanced and sophisticated methodologies in the formulation of these products (Fig. 5).

"Fish oil" is relevant as a traditional source of omega-3, while the emergence of "chia oil" suggests a growing interest in plant-based alternatives. The specific mention of "DHA" highlights the particular attention given to this fatty acid, known for its benefits for brain and eye

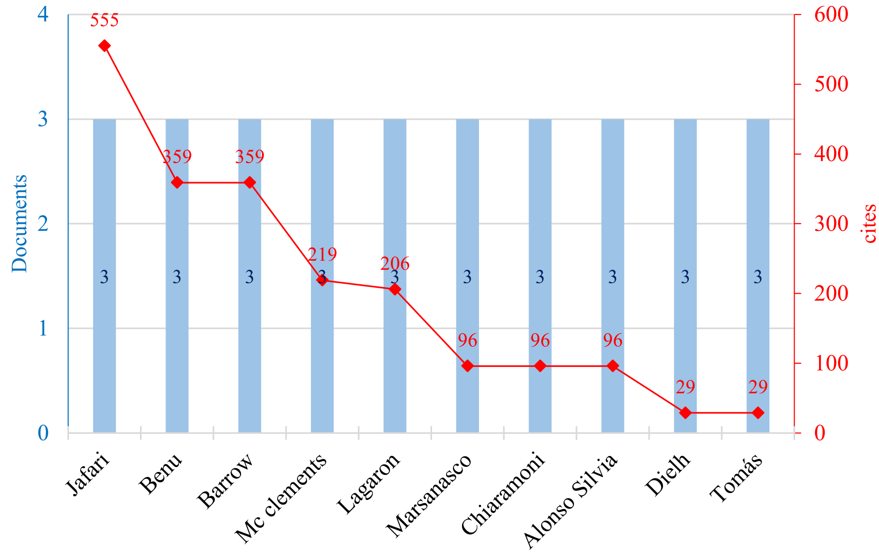

Fig. 4. Most Prolific Authors in Publications Focused on Omega-3 Fatty Acid Microencapsulation.

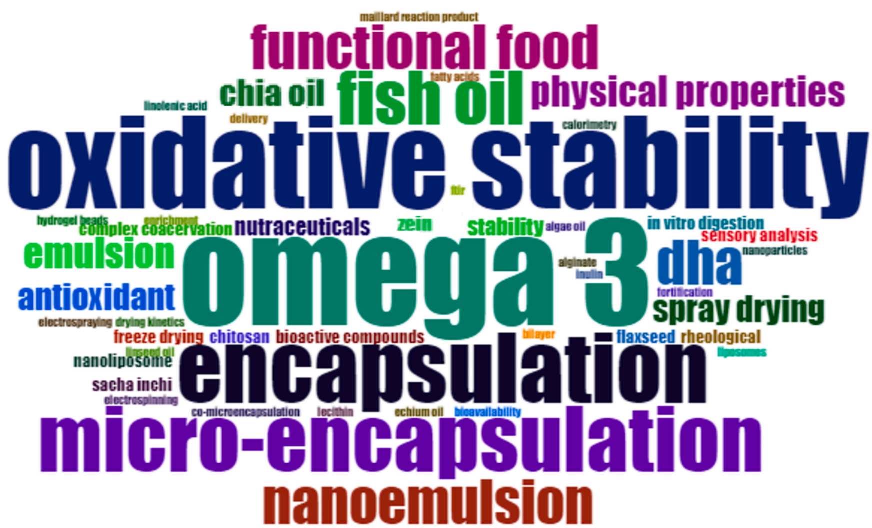

Fig. 5. Co-occurrence analysis of keywords in publications on the microencapsulation of omega-3 fatty acids.

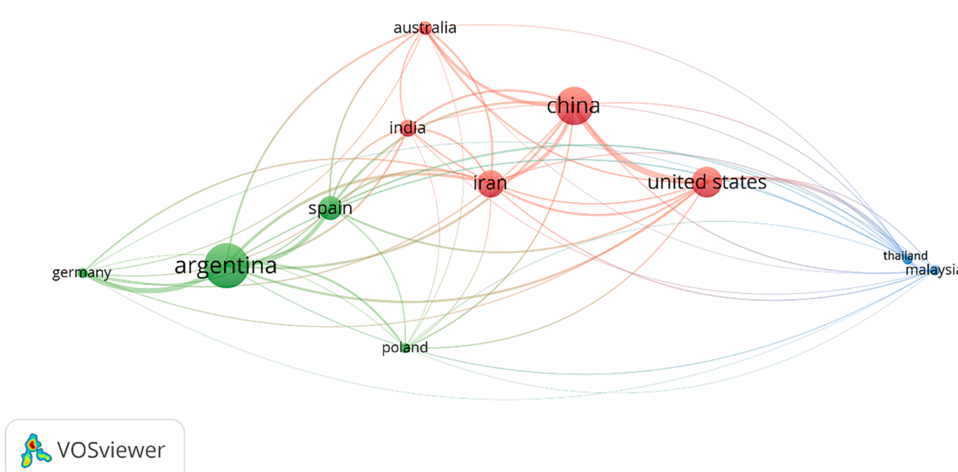

Fig. 6. International collaboration networks in publications on the microencapsulation of omega-3 fatty acids.

health (Abbas et al., 2023; Mun et al., 2019). The presence of terms like "physical properties," "emulsion," and "antioxidant" in the keyword list reflects the multidisciplinary nature of the research, covering aspects ranging from the physical characterization of foods to strategies for preventing oxidation.

3.1.6. International collaboration networks

The analysis of international collaboration networks reveals the formation of three distinct and complementary research ecosystems (Fig. 6). The first cluster, which includes China, Australia, India, Iran, and the United States, focuses on technological innovation and the development of new products, leveraging the diverse resources and technological capabilities of these nations (Orozco Colonia et al., 2020). On the other hand, the second cluster, consisting of Argentina, Germany, Poland, and Spain, shows a focus on studies related to bioavailability and health effects, likely benefiting from European expertise in clinical and nutritional research (Julibert et al., 2019; Ruperto et al., 2022; Saglimbene et al., 2019). The third cluster, which includes Malaysia and Thailand, suggests a specialization in the use of tropical marine resources, taking advantage of the rich biodiversity in the Southeast Asia region (Kang et al., 2016; Surachat et al., 2022; Trieu et al., 2023). This structure of international collaboration not only reflects a trend toward transnational and multidisciplinary research but also emphasizes the importance of global cooperation in addressing the complex challenges associated with the development of functional foods. As noted by Rosenthal et al. (2021), such international collaboration is crucial for fostering innovation and overcoming barriers in emerging and multifaceted research fields like functional foods.

3.1.7. Emerging thematic areas

The analysis of keyword co-occurrence and its temporal evolution reflects the progression of research. Between 2013 and 2014, the focus was on raw materials, with terms such as "gelatin" and "tuna" predominating in the literature, suggesting an initial emphasis on identifying and characterizing sources of omega-3. As the field progressed, between 2014 and 2016, there was a notable shift towards encapsulation techniques, with terms such as "microencapsulation" and "encapsulation" emerging. This shift indicates a growing interest in developing methods to protect and stabilize omega-3 fatty acids in food matrices.

The period from 2016 to 2018 marked a new phase, focusing on the characterization of fatty acids and their stability. The frequent appearance of terms like "omega-3 fatty acid" and "oxidative stability" highlights the need to understand the chemical behavior and preservation of these bioactive compounds.

Finally, from 2018 to 2021, a clear integration of more advanced chemical and technological aspects is observed, evidenced by the prominence of terms such as "chemistry" and "nanotechnology." This evolution suggests a growing sophistication in research approaches, incorporating innovative technologies to address the challenges in the field.

This thematic progression clearly illustrates how the field has matured, transitioning from fundamental studies focused on raw materials and basic encapsulation techniques to more sophisticated applications. Such evolution not only reflects the growth of knowledge in the area but also anticipates future research, where the convergence of advanced chemistry, nanotechnology, and other emerging disciplines will play a crucial role in the development of the next generation of omega-3 enriched functional foods.

3.2. Microencapsulation as a technique to protect omega-3 fatty acids

Microencapsulation is a widely studied and applied technique in various fields, especially in the food industry, where it serves to protect active compounds from external environmental factors (Espinoza-Espinoza et al., 2024). Various studies have determined that environmental conditions such as light, oxygen, humidity, and temperature are intrinsic factors that affect nutrients, compromising their quality and accelerating their degradation (Nole-Jaramillo et al., 2024; Yang et al., 2024). Furthermore, this technique prevents autooxidation reactions, meaning that the direct combination of food matrices, such as dairy products, with nutrients leads to undesirable conditions in the food, which results in consumer rejection of the product and a short shelf life of the microencapsulated excipients (Damerau, Mustonen, et al., 2022; García et al., 2022).

Additionally, microencapsulation has proven useful even for lipid compounds like fatty acids, being utilized to extend shelf life, prevent chemical damage during industrial processing, and maintain appropriate oxidative stability (De-la-Haba et al., 2023; Fadel et al., 2020). Through bibliometric analysis, sources of omega-3 fatty acids subjected to microencapsulation processes were identified, originating from the animal, plant, and protist kingdoms. The research findings are described in Tables 1, 2, and 3, highlighting the various techniques involved in microcapsule morphology, oxidative stability, efficiency, and zeta potential.

3.2.1. Omega-3 encapsulation using animal sources

Omega-3 fatty acids are long-chain polyunsaturated fatty compounds found in greatest abundance in marine animals. When consumed as part of a balanced diet, they support bioactivity in cardiovascular systems and have been associated with benefits in degenerative, anti-inflammatory, and antidiabetic conditions (Chang et al., 2021; Damerau, Mustonen, et al., 2022). This study identified several marine species used for the extraction of omega-3 fatty acids, including *Sardina pilchardus, Thunnus thynnus, Scomber scombrus, Batomorphi, Gadus morhua, Osmerus eperlanus, Rachycentron canadum, Oratosquilla nepa,* and *Clupeonella delicatula caspia* (Annamalai et al., 2015; Lamas & Álvarez, 2023; Selim et al., 2021)..

3.2.1.1. Core or source of encapsulation. Fig. 7.

The marine sources identified in this review and described above were presented in various forms, such as fish oil, fish liver oil, lipid extracts from waste, and fish protein hydrolysates. Fig. 8 shows that the most prevalent forms of omega-3 used for microencapsulation are fish oil and fish liver oil. This preference may be related to the lipid quality of polyunsaturated fatty acids such as DHA (docosahexaenoic acid) and EPA (eicosapentaenoic acid), and the bioactivity promoted by this lipid quality when transferred to the human body (Gowda et al., 2022). In such cases, it has been documented that adequate consumption of lipid compounds contributes to enhanced intellectual and cognitive development, protection against inflammatory processes, and degenerative diseases (Damerau et al., 2022; Lamas & Álvarez, 2023; Selim et al., 2021). On the other hand, the use of marine by products (waste) as a source of omega-3 represents an important opportunity for research. Key motivations include researcher's commitment to reducing environmental impact, the low cost of raw materials, the presence of valuable lipid compounds, and the valorization of production chains. These factors have led to the development of promising forms for the food industry, such as lipid extracts and hydrolysates (Amiri et al., 2024; Jamshidi et al., 2018).

3.2.1.2. Encapsulation technique. The encapsulation technique identified in the selected articles range from techno-physical processes, techno-physical processes, considering the application of emerging technologies and the structural behavior of encapsulated materials under processing conditions such as temperature, humidity, and pressure. Within this category, techniques such as spray drying, freeze drying, electrospraying, and microfluidization were identified. In contrast, physicochemical techniques involve the formation of coatings through electrostatic and molecular interactions, as well as interfacial precipitation, in combination with biopolymers and surfactants. Techniques in this category include emulsification, complex coacervation, and ionic

Table 1
Microcapsules loaded with foods from the animal kingdom.

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP (mV)	Oxidation	Fatty acids	References
1	S	SHE FO FPH	1% FPH (w/w) + 1% FO (w/w) + 0.1% SHE (w/w) + 5% SL (w/w) + WPC (1:1)	Freeze drying	38.12 nm	Particles were spherical in shape	97.58	-41.45 a -58.6	Particles with WPC showed less oxidation than those composed of CH	Nanocapsules retained a significant amount of PUFA	(Amiri et al., 2024)
2	S	Fish oil	Cellulose and SP	Emulsification and spray drying	-	The microcapsules masked the odor of the FO and did not have a greasy appearance	-	-	There were low values of water activity, indicating its stability against lipid oxidation.	-	(Di Giorgio et al., 2023)
3	S	Refined skate liver oil	SoA (1:3) O (10g): W	External gelation	-	Spherical	95	-	PV was low until the 7th day of storage.	EPA (219,70 - 230,05 mg/100g) and DHA (653,66 - 708,0 mg/100g)	(Lamas & Álvarez, 2023)
4	S	Baltic herring oil	15 % (w/v) BHO + 7,5 % (w/v) RPC + 7,5 % (w/v) WPC	Emulsification and spray drying	D 3,2 (47,55–49,30 µm) D 4,3 (98,13–125,25 µm)	Spherical with porous structure and varied sizes	40,9 - 49,67	-	Encapsulation increased stability, and the pH of the emulsions affects the OSI.	DHA: 11.1%, EPA: 7.8% in BH oil. No difference was found between the free and encapsulated oil.	(Damerau, Ogrodowska, et al., 2022)
5	S	Commercial cod liver oil	Plant protein + maltodextrin + whey protein	Emulsification and spray drying	-	Irregular-shaped pearls	57.27 % - 69.64 %	-	The increase in oil content had a negative impact on oxidative stability.	DHA: 14,29% to 14,57% EPA: 9,77% to 10,22% in SDEM n– 3: 26.85 to 27.64%	(Damerau, Mustonen, et al., 2022)
6	S	Fish oil	SP:FO 4:1	Emulsification and spray drying	-	-	370.5 and 563 g/kg 669.3 and 887.4 g/kg	-	Porous structure, greater interaction with oxygen.	-	(Di Giorgio et al., 2022)
7	S	Cobia liver oil	CH/STP:CBLO (0:1, 0.25:1, 0.5:1, 0.75:1, 1:1, y 1.25:1)	Emulsification and ionic gelation of chitosan with sodium tripolyphosphate	26 ± 136 nm and 347 ± 118 nm	Amorphous spherical structure with a high degree of crystallinity did not allow a regular arrangement of the polymer network	25,93% - 50,27% (+ CBLO = -EE)	The ZP decreased as the ratio between CBLO and CS increased.	The nanoparticles prevent the generation of hydroperoxides and secondary oxidation products after four weeks of storage.	DHA and EPA	(Chang et al., 2021)
8	S	Smelt	WPC, AG and MD 1:3 (Core: wall) 30% emulsion of dissolved solids (w/w)	Spray drying	-	-	71,71%, 68,61% and 64,71% (PS, AG, MA) >EE in PS	Less oxidation was observed in the oils encapsulated with WP.	Peroxides from 0 to 1.63 meq/kg.	MUFA: 4,04 PUFA: 51,46% DHA: 6,27 to 5,40%	(Selim et al., 2021)
		Sardine							Peroxides of 3.52 meq/kg.	MUFA: 29,13 PUFA: 43,09% DHA: 6,27 to 5,40%	
		Mackerel							Peroxides of 5.32 meq/kg.	MUFA: 47,79 PUFA: 31,07% DHA: 6,27 to 5,40	
9	S	Tuna oil	PG 2.5% and PGU 9% (w/w)	Coarse emulsion: O:W 10:90 Microfluidization: 110 MPa with 4 cycles	PGU 2.5%: ~21 nm PG 9%: 127,9 ± 3,1 nm	Fine particles, uniformly distributed.	PGU2.5: 96,38 ± 1,78% PG9: 95,83 ± 1,74	PGU 2.5%: -31.6 ± 0.6 PG 9%: -19.0 ± 0.2	PGU 2.5%: 7.87 ± 0.24 meq/kg of oil and PG 9%: 9.84 ± 0.69 meq/kg of oil.	The DHA and EPA content was 31.383%.	(Shehzad et al., 2021)

(continued on next page)

Table 1 (*continued*)

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP (mV)	Oxidation	Fatty acids	References
10	S	Fish oil highly enriched with DHA	Z: FO 2:1 (w/w) (Oil + 855 ethanol containing 4.5% of Z)	Electrospraying assisted by pressurized gas	Empty capsule: 3.7 ± 1.8 µm Loaded capsule: 1.4 ± 0.8 µm smaller	Irregular structure with diffuse edges.	84 ± 1%	-	Initial PV of ~1.5 meq/kg and final PV of 19-22 meq/kg. Oxidative reactions started after 7 days at 5°C.	-	(Busolo et al., 2019)
11	S	Mantis shrimp oil *(Oratosquilla nepa)*	MSO: 10% H_2O distilled: 90% (5% of S: T ratio 40:60)	Coarse emulsion: 20,000 rpm for 2 minutes Fine emulsion: Ultrasound for 10 minutes	190 to 240 nm The diameter increased with the storage time (25 days)	Shape of spheres and uniform sizes	-	-42 to -71 ZP decreases as the concentration of T increases	Gradual increase in oxidation over storage time.	(EPA; C20:5n3): 1.1±0.2 g/100 g lipids (DHA; C22:6n3): 14±1 g/100 g lipids Oleic acid (C18:1): 32±3 g/100 g lipids	(Chaijan & Panpipat, 2019)
12	S	Kilka oil *(Clupeonella delicatula caspia)*	CH: MS 1%: 9%, KO (20% w/w) ratio 1:4 (w/w)	Emulsion (5000 rpm x 30 min) and Freeze drying (72h)	2.30 to 4.73 µm	Irregular shape with significantly sharp edges. Free of cracks and pores.	88	-	-	C20: 5n-3 (EPA)7.03 ± 0.29% C22: 5n-3 (DPA)1.29 ± 0.10% 22: 6n-3 (DHA)16.1 ± 1.34% ω3/ω6 = 1.4%	(Hasani et al., 2019)
13	S	Sardine oil	SO (30 % w/w), T2 (0,25% w/v). Va-gCh 0,8% (w/v)	Spray drying (TE: 140°C and TS: 77°C)	2,3 µm	Spherical and irregular with small pores on the smooth surface.	84 ± 0,84%	-	-	Polyunsaturated n-3 fatty acids such as EPA and DHA.	(Vishnu et al., 2018)
14	S	Fish oil and γ-oryzanol	γO:FO:SCT:CM Oil phase: 0.1g:3:7 (10g) +10g T:S2 3:1 (w/w) Aqueous phase: 80g sol. 1% CA and 0,1% SB	Nanoemulsion drop by drop under constant stirring	152 nm	-	-	-	Peroxide index (0.65 mmol/L) was 1.8 times higher after 21 days.	The contents of EPA and DHA decreased with the increase in storage time.	(Zhong et al., 2018)
15	S	Fish protein hydrolysate and fish oil	CO= Fuc:WPC 30:70 F1: FPH:NaCl:H_2O 4g:0,5g:25,5 F2: PGPR:FO 6,28g:63,72g W1/O=F1:F2 30:70 W1/O:CO 30:70	Emulsion and Freeze drying	-	Porous and smooth structures	86,31 ± 2,02	-	PV gradually increased after weeks 6 and 7 of storage.	C18:1n9 (19,565–20,380%) C16:0 (11,217–11,536%) DHA: 18,70 and 21,32 g/100 g FAME EPA:15,44–17,13 g/100 g FAME	(Jamshidi et al., 2018)
16	S	Cod liver oil	P:T:FO 17%:20%:10% + Antioxidants A: 500 ppm of δT and 500 ppm of RE	Electrospinning	0.773 and 0.786 um	Beads interspersed along the fibers	10% of oil: 88.5 ±0.7%	-	Stability improved with the addition of antioxidants; however, an excess of antioxidants promoted prooxidation.	-	(García-Moreno et al., 2017)
17	S	Fish oil	Nanoliposomes, lecithin, sunflower oil, and fish oil	Nanoencapsulation	300-500 nm	-	92,22 ±0,19 %	-	PV remained stable and constant during the 21-day storage period.	-	(Ghorbanzade et al., 2017)
18	S	Fish oil	CO=G:AG 1:1 CO:FO 1,5%:3%	Complex Coacervation and Freeze drying	>0.5 um	Round shape with multinucleated structure	76.66 ±0.16%	-	-	18,18% de EPA and 12,82% de DHA	(Habibi et al., 2017)
19	S	Fish oil containing EPA and DHA (3:2, 300 mg/g FO)	PUFA=EPA:DHA 3:2, w/w Soy lecithin:PUFA 0,4:2	ω3 Nanoliposomes	Nanoliposomes: 73,2 ± 18,1 nm Microcapsules: 2-11 µm	Spherical shape	-	0.216 y −48.33 mV	Breads containing microencapsulated and nanoliposomal ω3 PUFAs	-	(Rasti et al., 2017)

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Table 1 (*continued*)

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP (mV)	Oxidation	Fatty acids	References
			Microencapsulates contain 10.0% EPA and DHA						showed no additional oxidation during storage.		
20	S	Tuna oil and probiotic bacteria *Lactobacillus casei*	WPI:TO:PBLC:AG WPI:15g:5g:AG	Spray drying and Freeze drying	-	Freeze drying: Microcapsules with a highly porous structure Spray drying: Microcapsules with a compact structure, fewer pores, and less surface oil.	-	-	Spray-dried co-microcapsules containing *L. casei* and tuna oil exhibited better oxidative stability. PV increased with longer storage time.	DHA:29.4% PA: 19.2% OA: 6.0% SA: 5.3% MA: 2.4% AA: 2.0% DA: 1.2% LA: 1,2% StA: 0,6% LiA: 0,4%	(Eratte et al., 2016)
N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP (mV)	Oxidation	Fatty acids	References
21	S	Cod liver oil	CLO:FG:MD:GEO 1%:2%:2%:0.25%	Spray drying	15 and 13 µm	Variation in sizes. Spherical shape with wrinkles on the surface	Higher encapsulation efficiency with only maltodextrin at 49.34%	-	The oxidative stability of the encapsulates showed better protection against oxidation (1.89 mg of malondialdehyde/kg).	The highest PUFA content was found in the CLO + maltodextrin encapsulates (8.92%), followed by CLO + fish gelatin (8.71%).	(Annamalai et al., 2015)
22	S	Fish oil (polyunsaturated ω-3 oils)	Organic phase: FO (0-10% w/w) + LeO (0-10% w/w) + T (2.5-10% w/w) Aqueous phase: buffer solution at pH 3.0	Spontaneous emulsification	d < 200 nm	Monomodal size distribution.	-	-	-	-	(Gulotta et al., 2014)
23	S	Tuna oil rich in omega-3 fatty acids	WPI-AG 3:1 For complex coacervation (optimal pH of 3.75)	Complex coacervation and freeze-drying	-	Freeze-dried microcapsules with a porous surface.	72,95%	16.80 at pH 3.0 −20.21 at pH 7.0	OSI: 13.2 h	The oil contained 39.03% omega-3 fatty acids.	(Eratte et al., 2014)
				Spray drying		Spray-dried microcapsules showed no pores on their surface.	>85%		OSI: 22.1h		
24	S	Tuna oil	G:SHMP 15:1 At pH 4,7	Complex coacervation (crosslinking with transglutaminase) and freeze-drying	50–80 µm	Microcapsules with a multiple core. Non-spherical shape.	EE of 99.82% and a payload of 52.56%.	Gelatin product + SHMP: mV (-) pH ranges from 4.0 to 7.0	Duralox Blend AN 110 XT at 1.2% (w/w) in tuna oil provides the best stability. Microcapsules OSI: 39.32 ± 1.50 h and 40.16 ± 1.27 h.	-	(Wang et al., 2014a)
25	S	Docosahexaenoic acid (DHA)	ZCP: DHA 2:1	Electrospraying	490 ± 200 nm for zein-DHA	Rounded size and morphology. Sheets of irregular ultrafine zein-based pearls.	-	-	At 37°C, ultrafine encapsulation delayed DHA degradation and oxidation.	-	(Torres-Giner et al., 2010)
26	W	Aceite de pescado	GS:WPC 80:20 w/w FO 13% by weight	Pressurized gas-assisted electrospraying in coaxial configuration	4.2 – 4.9 µm	Water did not evaporate from the core, allowing the formation of	50	-	The FO was infused through the core, which prevents temperature rise and oxygen transfer.	-	(Rahmani-Manglano et al., 2024)

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Table 1 (*continued*)

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP (mV)	Oxidation	Fatty acids	References
						spherical microcapsules and smooth surfaces.					
27	W	Fish oil	C:EW:FO:FPH 1:2:2:2 w/w/ w/w	High temperature heat drying	-	The stable colloidal form of the fish oil was granted by an efficient trapping between C and EW.	-	-57.60	Low solubility is a key indicator of oxidation, since it prevents undesirable flavors.	Unsaturated fatty acids accounted for 73.5% of the total fat extracted.	(Gómez-Guillén et al., 2023)
28	W	Tuna oil	TO 2% (w/w) Lipasas	Complex coacervation	575 nm	The particles were spherical, agglomerated and in some cases elongated.	-	13.53	The emulsion with gelatin and acylglycerol was more prone to intense complex coacervation reactions, which contributed to the formation of microcapsules with a denser structure.	-	(Xuan et al., 2023)
29	W	Fish oil	Denatured WPI	-	-	-	-	-	DHA oil encapsulation triggered a more efficient absorption of DHA and preserved its oxidative quality.	-	(Wang et al., 2022)
30	P	Fish oil	Phases Oleous: Aqueous 10:1	Double channel microfluidization	160 nm	Drop size, polydispersity and apparent viscosity of the emulsions increased with increasing oil content.	-	-90	The oxidative stability of the emulsions depended on the nature of the emulsifier coating the lipid droplets.	-	(Liu et al., 2016)
31	P	Fish oil	SSPS:MD 1:6.5 Core:Coating 1:4	Spray drying followed by film coating	400 – 500 µm	Round particles were obtained with agglomerations on the surface and some insignificant eruptions	96.44	-	There was no significant oxidation for 6 weeks at a temperature of 3 to 4°C.	A high concentration of PUFAs increased the development of PV and propanal during storage.	(Anwar et al., 2010)
32	P	Fish oil	WPI 20% solution (w/w) WPI:FO 2:1	Spray drying with a 2-channel ultrasonic nozzle	11.3 µm	Round particles with irregular shapes were produced due to nozzle clogging during the drying process and showed narrow particle size distribution	76.1	-	These nozzles cause the FO and WPI to flow through separate channels and do not mix until they meet at the nozzle, minimizing oxidation of the oil.	-	(Legako & Dunford, 2010)

SHE: shrimp lipid extract FO: fish oil, AO: algal oil, TO: tuna oil, SO: sardine oil, KO: Kikka oil, MSO: Mantis shrimp oil, HOB: herring oil, CLO: cod liver oil, FPH: fish protein hydrolysate, SoA: sodium alginate, RPC: rice protein concentrate, WPC: whey protein concentrate, SP: soy protein, SL: soy lecithin, CH: chitosan, Va-gCh: chitosan grafted with vanillic acid, STP: sodium tryptophosphate, AG: gum arabic, MD: maltodextrin, PG: Purity Gum, PGU: Purity Gum Ultra, S: Span 80, T: Tween 80, T2: Tween 20, Z: zein, γO: γ-oryzanol, δT: δ-tocopherol SCT: Short Chain Triglycerides, CM: wall material, CA: citric acid, SB: sodium benzoate, FUC: fucoidan, PGPR: polyglycerol polyricinoleate, FAME: fatty acid methyl esters, G: gelatin, P: polulan, RE: rosemary extract, PBLC: probiotic bacterium Lactobacillus casei, DHA: docosahexaenoic acid, EPA: eicosapentaenoic acid, PA: palmitic acid, OA, oleic acid, SA: stearic acid, MA: myristic acid, AA: arachidonic acid, DA: decosapentaenoic acid, LA: linoleic acid, StA: stearidonic acid, LiA: linolenic acid, FG: fish gelatin, GEO: ginger essential oil, LeO: lemon oil, SHMP: sodium hexametaphosphate, ZCP: Zein corn prolamin OSI: Oxidative Stability Index, WPI: whey protein isolate, C: carrageenan, EW: egg white, GS: glucose syrup, SSPS: soluble soy polysaccharide; DB: Databases, S: Scopus, W: Web of science and P: Pubmed

Table 2
Microcapsules are loaded with foods from the plant kingdom.

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP (mV)	Oxidation	Fatty acids	Digestibility	References
1	S	Soybean and Walnut Oil	The mass ratio of nanoemulsion/XA of 1:3	High-pressure homogenization	150 μm	The flow behavior was characterized by a linear variation between shear stress and shear rate; that is, Newtonian behavior.	-	-	The viscoelastic modules increased with the xanthan gum concentration due to the existence of polymer entanglements.	-	-	(Alfaro-Rodríguez et al., 2022)
2	S	Canola Oil	WPI:DX6 at 3% (w/w)	Freeze drying	1.24 mm	The molecular weight of DX produces smaller conjugates. Small molecules can organize at the interface, producing stable emulsions.	62.9	-	The hydrophobic groups of the protein are able to adsorb the lipid phase, and the polysaccharide chains (which are strongly hydrophilic) can easily solvate the aqueous medium.	-		(Loyeau et al., 2021)
3	S	Chia Seed Oil	WPC:SPI: AG=Coating 8:1:1 (w/w):(w/w):(w/w) Coating:CSO 2:1 (w/w)	Complex coacervation and Freeze drying	7.39 – 2.30 μm	The presence of thick membranes around the oil droplets induces physical stability of the microcapsules after Freeze drying .	79.88	-	No distortions were observed between the spectra, highlighting the predominance of physical interactions between the core and the wall material.	The microencapsulation process preserved the chemical quality of the CSO.	-	(Bordón et al., 2023)
4	S	Chia Oil	SC/L	Spray drying	11.3 – 14.8 μm	Spherical	97	-	The incorporation of ascorbyl palmitate maintained the PV for 2 months.	-	-	(Ixtaina et al., 2022)
5	S	Chia and Sunflower Oil	MD/BM	Ultra-high-pressure homogenization	0.30 – 5.93 μm	Polar lipids and proteins create a spherical coating.	70 – 90	-28 – -22	The stability in (TSI) did not indicate particle destabilization.	-	-	(Aghababaei et al., 2021)
6	S	Cold-pressed Chia Seed Oil	CSO:PC:CH:MD 5%:1%:0.2%:20% (w/w)	Electrostatic layer-by-layer deposition	Various sizes, less than 100 μm	Sheet-like structures, rough walls with protrusions.	88.97	+55	The double protective layer of the oil kept the PV < 10 for 40 days.	Methyl –CH_3 groups, n-3, and olefinic –CH=CH– groups were identified.	-	(Julio et al., 2019)
			CSO:DL:CH:MD 5%:1%:0.2%:20% (w/w)				96.86	+47				
7	S	Chia Seed Oil	SC:L:CSO 10%:10%:15% (w/w)	Pre-emulsification and spray drying	0.25 to 6.47 μm	Spherical microcapsules with smooth surfaces.	99.79	-	The MRPs at 100°C protected the oil from lipid oxidation (PV: 6.25).	The content of ω-3 PUFAs remained stable at 61.47 – 62.63%.	-	(Copado et al., 2019)

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP	Oxidation	Fatty acids	Digestibility	References
8	S	Chia seed oil	Ratio TS:CSO 2%:5%	Spontaneous emulsification	> 2.5 μm	-	-	-	The peroxide index (1.6 mmol/kg) met the technical requirements.	The main fatty acid was linolenic acid (59.35%), which was higher than in flaxseed oil (56.68%).	-	(Teng et al., 2018)
			Ratio TS:CSO 0.5%:5%	Microfluidization		Stable microcapsules at room temperature for 2 weeks	-	-				
			SC:CSO 0.5%:5%		0.16 μm	Stable microcapsules at 4°C for 2 weeks	-	-				
			CSO:P90:HL:PE:G:PP:S 6:2.2:0.8:0.5:18:16.5 %:%:%:%:%:%			Fine microcapsules stable at 37°C for 2 weeks	-	-				
9	S	Echium seed oil	Pul-PPI: 10% PPI: 30% of Pul Pec: 20% of Pul-PPI	Electrospinning	190 nm	Coarse microfibers were evidenced, with larger diameters and significant	68.7	-45.2	Protection of up to 3 times the oxidation time was evidenced.	-	94% was released in 160 min and its efficiency was	(Najafi et al., 2022)

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Table 2 (*continued*)

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP	Oxidation	Fatty acids	Digestibility	References
			T: 10%; SE: 1% EO: saffron oil			viscosity compared to other formulations					prolonged for 171 days	
10	S	Echium oil	Oil phase: O LA:PA:SA =25% in weight EO=75% in weight Aqueous phase: W WPI=2% in weight O:W 1:9 (w/w)	Simple emulsion by rapid cooling process	0.2 µm	Microcapsules with a donut shape and small pores on the surface	78	−35 at −55	The addition of lipid carriers significantly reduced the oxidation of EO.	Lipid carriers protected the PUFAs through a compact structure	-	(Azizi et al., 2018)
11	S		Ge:AG 1:1 0.075 g of SiA/g of Ge	Complex coacervation	40.79 µm	Microcapsules smaller than 100 µm can be applied in food	-	-	Oxidative stability increased with the concentration of phenolic compound.	-	There was greater release in the intestinal system.	(Comunian et al., 2017)
12	S	Dried common bean	β-cyclodextrin was used as the coating material	Kneading	-	-	60-42	-	β-CD complexes have higher thermal and oxidative stability.	Linoleic acid was the main component.	After 4 hours, 24.4% of the oil was released	(David et al., 2019)
13	S	Vitamins C and E	SPC:SA (1:0.25 molar ratio) Vitamin concentration: 22.4 mM	Dehydration-rehydration	µm	SPC:SA liposomes can be selected as food additives.	52.3 – 41.7	-36.62	SA improved stability against peroxidation.	Fatty acids immobilized the alkyl chains of the bilayer.	-	(Marsanasco, Calabro, et al., 2015)
14	S	Vitamin E and folic acid	SPC:SA (1:0.25 molar ratio) Vitamin concentration: 22.4 mM FA: concentration of 0.136 mM	Dehydration-rehydration	54.05 µm	The size and aggregation tendency remained stable for 28 days at 4°C	97.1	-	Rigidity affects the propagation of radical initiation, reduces water flow, and prevents oxidation.	-	-	(Marsanasco, Márquez, et al., 2015)
15	S	Vitamin E and tocopherol	SPC:SA (1:0.25 molar ratio) Vitamin concentration: 22.4 mM	Dehydration-rehydration	166 µm	Laminar structure with a central core in both spherical and non-spherical forms	-	14.52	The rigidity of 1,2-dipalmitoyl-sn-glycero-3-phosphatidylcholine in the hydrophilic-hydrophobic region reduces the water flow rate	-		(Marsanasco et al., 2015)
16	S	Flaxseed oil	PAGE at 0.05%:Ch at 1%. 1:3 LO:Biopolymers 1:20	Complex coacervation	540 µm	Under these conditions, the microcapsules were the largest and most uniform.	89	31.12	No substantial distinction of microspheres was observed throughout the storage time.	The main fatty acids identified were oleic, linoleic, palmitic and stearic acids	The release rate reached 22.74% at the end of the release time.	(Dabiri Movahed et al., 2024)
17	S	Flaxseed oil	LO:FSG 0.25:1	Drip process	-	The microcapsules were spherical in shape and with agglomerations.	97		The FSG coating was ideal for providing oil stability	-	-	(Elsorady et al., 2024)
18	S	Flaxseed oil	LO:MD:CH 10:20:1.5 Units of materials: g/100g	Spray drying	-	Microcapsules with low efficiency have free oil on their surface, which is susceptible to oxidation, causing high PV values	80.10	-	The PV was in an acceptable range (5.69-8.13 meqO_2/kg) compared to bulk oil	The predominant fatty acids were: linolenic, oleic, linoleic, palmitic, and stearic. Stable for up to 30 days	Flaxseed oil was released quickly within 2 hours, then stabilized, causing a burst effect.	(Kanwal et al., 2021)
19	S	Flaxseed oil	Emulsion 1 Aqueous phase: W WPC:MD 2%:20% Oily phase: O = LO W:O 80%:20% Emulsion 2	Ultrasound-assisted nanoemulsion	0.464 µm	The oil is inside the WP/SA double protective layer, and this structure could be supported by the coating matrix	70	-45.5	The negative charge can be attributed to the anionic components of the WPC/SoA complex.	Targeted administration of nanoemulsions loaded with LO improved the fatty acid profile by increasing its content	Alginate increases gastric viscosity, which could restrict pepsin diffusion	(Abbasi et al., 2019)

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Table 2 (*continued*)

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP	Oxidation	Fatty acids	Digestibility	References
20	S	Flaxseed oil	LO:WPC:SoA:MD 10%:1%:0.25%:10% JSS:WPI ratio 3:1 Oil load 30%	Spray drying	-	Increasing the oil load and the inlet air temperature resulted in a higher peroxide value and lower moisture content	82.56	-	The high drying temperature disrupted the water evaporation and film formation, leading to oxidation	-	-	(Bhushan et al., 2017)
21	S	Flaxseed oil	LO:SoA:SC 2%:0.8:4% (w/w):(w/w):(w/w)	Crosslinking	1069 μm	Hydrogel pearls were physically stable when stored at 55°C for 14 days	-	-	Hydrogel pearls rich in antioxidants are an effective medium for protecting omega-3 fatty acids from oxidation	-	-	(Chen et al., 2017)

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP (mV)	Oxidation	Fatty acids	Digestibility	References
22	S	Flaxseed oil	LO:SoA:SC 2%:0.8:2% (w/w):(w/w):(w/w)	Spray drying	Initial phase 581.2 μm	The presence of caseinate within the alginate droplets used to form microgels increased their dimensions.	-	Initial phase -25.0	The present study indicates that these delivery systems are still capable of releasing flaxseed oil within the gastrointestinal tract, albeit at a slower rate for microgels.	-	The stability of the nanoemulsions is due to electrostatic repulsions between the lipid droplets with high charge.	(Chen, Fan, et al., 2017)
					Oral phase 615.4 μm	The microgels adsorbed a layer of mucin molecules on their surfaces	-	Oral phase -25.0			The increase in size is due to different flocculation's because of osmotic attraction.	
					Gastric phase 509.2 μm	The contraction of the microgels in highly acidic gastric fluids is due to the reduction of repulsions between the alginate chains.	-	Gastric phase -5.0			The origin of this size is attributed to the low pH and high ionic strength of the simulated gastric fluids, as well as the presence of pepsin and mucin.	
					Intestinal phase 590.3 μm	At neutral pH, alginate molecules have a negative charge, causing strong repulsion and separation of the molecules	-	Intestinal phase -28.0			The large particles are a mixture of lipid droplets, proteins, insoluble calcium salts, and long-chain fatty acids.	
23	S	Flaxseed oil	LO:GMS:P6:T:1PP:Q 6%:4%:5%:5%:2%:0.1%	High-pressure homogenization	0.892 μm	The solubility of quercetin in hydrophilic matrices composed of flaxseed oil and surfactants was improved by at least 1300 times.	95.94	-16.7	The presence of quercetin in the surfactant layer of the lipid matrix confirms the delay in oxidation.	Due to its antioxidant property, quercetin would protect unsaturated fatty acids from oxidation.	Around 12-25% of the quercetin was released within the first 2 hours.	(Huang et al., 2017)
24	S	Flaxseed oil	AG:MD:LO:SL 72:56:33:5 g:g:g:g	Spray drying	10 – 50 μm	The wall materials resulted in a more permeable and wrinkled wall matrix.	91.4	-	The encapsulation system has minimized lipid oxidation by interfering with oxygen permeation.	The ALA content was not affected by the microencapsulation process.	-	(Gallardo et al., 2013)

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N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP (mV)	Oxidation	Fatty acids	Digestibility	References
25	S	Penoia arborea seed oil	TPSO:WPI:SoA 5%:0.45%:0.5%	Layer-by-layer self-assembly	1.291 µm	The high viscosity of SoA significantly contributed to the stability of the bilayer emulsion.	90.2	-31	Monolayer emulsions are less stable and prone to oxidation.	The digestion of the bilayer emulsion occurred in the intestinal phase, with fatty acid release rates and ALA bioaccessibility.	The droplet size of the monolayer emulsion increased due to the gradual hydrolysis of WPI by pepsin, which broke and exposed the oil droplets.	(He et al., 2023)
26	S	Kenaf seed oil	Material concentration: 30% AG:SC:β-CD 4:1:1 The concentration of KSO was 1/4 of the mass of the wall materials	Spray drying	-	The combination of wall materials strengthens the polymeric matrix by filling the space in the encapsulating matrix and reducing oxygen permeability.	90.01	17.3	The polymeric matrix slows down the migration of oil through the structure and the diffusion of oxygen.	The spray drying process did not affect the fatty acid profile.	-	(Chew et al., 2018)
27	S	Sacha Inchi seed oil	The oil amount was set at 5% w/w The wall material was set at 10% (85:15, MD:SC) T2: 1% + S:0.5%	Spray drying	0.31 µm	The use of elevated temperatures increases the stickiness of the microcapsules by directly degrading the wall materials, thus less dry matter is recovered.	70.28	-	The microcapsules showed lower moisture values, resulting in a longer shelf life under controlled conditions.	The microcapsules obtained showed concentrations of 1.45 M of Omega-3 fatty acids.	The microcapsule protected omega-3 acyl units compared to free oil under the same gastric conditions.	(Rodríguez-Cortina & Hernández-Carrión, 2023)
28	S	Sacha Inchi seed oil and natural extracts	AG:MD:WPI 3:13:3 The oil was added at a concentration of 33.33% (1 g of oil/3 g of encapsulating agent)	Spray drying	6.1 µm	The microcapsules exhibit shapes ranging from round to low agglomeration	88.62	-	Oxidative stability improved with antioxidant extracts from fruits like Camu Camu.	The values of polyunsaturated omega-3 fatty acids are close to those of the initial sample, confirming their preservation.	-	(Chasquibol et al., 2023)
29	S	Sacha Inchi seed oil	T:S 1%:0.5% MD:SC=Coating 80 (w/w):20 (w/w) SISO=Core 5% (w/w) Coating:Core 2:1	Spray drying	0,77 at 2,21 µm	A higher oil concentration increases viscosity, which helps resist the speed of the process and, therefore, recoalescence between the particles.	53,33–57,72	-	At higher protein concentrations, layers can form on the surface of the particles; these interfaces are large enough to counteract the attractive forces, causing repulsion between the droplets and improving the stability of the emulsion.	-	-	(Rodríguez-Cortina et al., 2022)
30	S	Sacha Inchi seed oil	T:LC=Surfactant 2:1 SISO: Surfactant=Core 30%:50% Core:Z 5%:15%	Freeze drying	3.27 µm	The zein microparticles loaded with SISO had a low content and spherical structure	59,94-72,29	-	A higher surfactant concentration improves oxidative stability and may extend shelf life up to 21 days.	-	-	(Suwannasang et al., 2021)

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Table 2 (*continued*)

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP (mV)	Oxidation	Fatty acids	Digestibility	References
31	S	Olive oil	DHA + OO Cremophor EL: PEG (1:2)	Simple agitation	52.9 nm	The nanoemulsion droplets formed a laminar structure without separation or incompatibility and spherical in shape.	-	-17	The formulation was stable under accelerated conditions such as room temperature for 3 months.	-	In vitro studies demonstrated 88.5% absorption of DHA at 5h.	(Tharmatt et al., 2021)
32	S	-	SC:MD =Coating 1:2 Coating:LPC+ALA 1% w/v:0.1% w/v	Ultrasonic sonication	50 nm	According to electron spin resonance spectroscopy measurements indicate the increase of microviscosity.	-	-30	After 21 days of storage the degree of oxidation was 10%.	LPC micelles hinder oxygen diffusion in the long term.	-	(Semenova et al., 2016)
33	S	Cold-pressed oils of canola, black cumin, wheat germ, evening primrose, and camelina, as well as rice bran oil.	Oils ω6:ω3 (5:1) F1: 50% A. rapeseed + 30% A. cumin + 20% A. wheat germ	Emulsion and Freeze drying	-	Spherical shape. Larger microcapsules provide better protection for the encapsulated material, but they dissolve less effectively in the final products.	-	-	The use of the encapsulation process resulted in reduced oxidative changes in the encapsulated oils observed during thermal treatment, especially in autolyzed yeast.	C18:3 7% in all blends SFA% F1: 11.38 ± 0.01 MUFA % F1:44.06 ± 1.30, PUFA% F1:44.56 ± 1.28, ω6/ω F1:5.05 ± 0.03,	-	(Cichocki et al., 2022)
34	W	Purified Chia seed oil	CSO:SL:SA 0.2g:48mg:0.6g	Spray nano-drying	0.16 µm	SA-protected particles were omega-3 rich oil vehicles for functional food design.	98.1	-	-	Smaller particles have a larger surface area exposed to the intestinal environment, leading to a greater disintegration of fatty acids.	-	(Álvarez et al., 2022)
35	W	Aceite de Chía	Porous starch pretreated by enzymatic hydrolysis: 2g CSO: 30-40%.	Vacuum impregnation	-	The microcapsules maintained their granular, rough and porous shape by swelling of the starch walls.	-	-	Starch treated with enzymatic hydrolysis had the ability to protect the core from oxidation.	Linolenic, linoleic, and oleic acids were abundant		(Piloni et al., 2022)
36	W	Chia oil and fish	CSO:FO 50%:50%	Spray drying	-	-	94	1.3	CSO has lower oxidative stability than FO due to differences in fatty acid composition. Therefore, ensuring stability will depend on optimizing both oils.	-	-	(Rahim et al., 2021, 2022)
38	W	Flaxseed oil	The particles were composed of multiple micro-ingredients.	Emulsification	798.76 nm	Particles showed stable nature, did not show breaks or holes on the surface	-	-26.96	The peroxide value was less than 1 meq/kg indicating the stability of the oil.	Stability was also reflected in the fatty acid composition, showing no instability.	-	(Jagtap et al., 2021)
39	W	Flaxseed oil	Polysaccharide gums at 25°C were used as wall material.	Spray drying	-	-	90.78	-	At 120°C as spray temperature, particles with higher stability were identified.	Linoleic acid represented 57% of the total fatty acid profile.	-	(Shahid et al., 2020)
40	W	Flaxseed oil	LO:WPI al 2% w/w 10%:90%	Ice bath assisted microemulsification	-	Particles were opaque white during the first days of storage. However, the surface part of the particles	-	49.1	The incorporation of compounds such as linseed lignan and secoisolariciresinol inhibit oxidation, while compounds such as p-coumaric	-	-	

(*continued on next page*)

Table 2 (*continued*)

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE%	ZP (mV)	Oxidation	Fatty acids	Digestibility	References
						turned yellow after 23 days.			acid and secoisolariciresinol diglucoside act as prooxidants, i.e. progressively promote fatty acid oxidation.			
41	W	Flaxseed oil/ algae oil	SL:Oil premix (Mix) 30:70 (g) Oil:T4:SL:Mix:H_2O 50:3:3:10:44 %:%:%:%:%	Ultrasound	120 nm	Lecithin forms larger droplets because the water droplets within the continuous phase disperse before the emulsifier can absorb to the surface.	-	-	The use of high refrigeration rates in the encapsulation process guaranteed the success of stability.	-	-	(Lane et al., 2016)
42	P	Hemp Seed Oil	Zeina 62.5 mg HSO: 250 mg	Freeze drying	491 nm	The microparticles are spherical and the size of each particle is not uniform. This high polydispersity is because HSO is composed of multiple components, and each compound is different.	26		The delay of oxidation increases as the thickness of the microcapsule increases, achieving oil stabilization over extended periods of time.	-	-	(Kim & Hwang, 2024)

ALA: α-linolenic acid, CSO: chia seed oil, EO: Echium oil, LO: flaxseed oil, SISO: Sacha Inchi seed oil, KSO: kenaf seed oil, OO: olive oil, HSO: hemp seed oil, PC: sunflower lecithin enriched with phosphatidylcholine, DL: deoiled sunflower lecithin, AG: gum arabic, AX: xanthan gum, SPC: soy phosphatidylcholine, SL: soy lecithin, WPC: whey protein concentrate, WPI: whey protein isolate, TPSO: Penoia arborea seed oil, SPI: soy protein isolate, SC: sodium caseinate, L: lactose, MD: maltodextrin, BM: whey powder, CH: chitosan, CM: coating material, T: tween 80, T2: tween 20, T4: tween 40, S: span 80, P90: sucrose monopalmitate, GMS: glyceryl monostearate, HL: hydrolyzed lecithin, PE: polyglycerol ester, G: glycerin, PP: propylene glycol, S: sorbitol, LA: lauric acid, PA: palmitic acid, SA: stearic acid, SiA: sinapic acid, Ge: gelatin, β-CD: β-cyclodextrin, FA: folic acid, SoA: sodium alginate, JSS: jack fruit, Q: quercetin, Z: zein, DX6: 6 kDa dextrose, PAGE: Prunus armeniaca gum, FSG: flaxseed gum, Pul: puluanum, PPI: pea protein isolate, Pec: pectin, SE: saffron extract, SELN: AE-loaded nanoliposomes, LPC: soybean lysophosphatidylcholine micelles, PEG 400: polyethylene glycol 400; DB: Databases, S: Scopus, W: Web of science and P: Pubmed

Table 3
Microcapsules loaded with foods from the protist kingdom.

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE %	ZP (mV)	Oxidation	Fatty acids	Digestibility	References
1	S	Algae oil	Ratio WG: AO 2:1	Electrospraying of emulsion assisted by pressurized gas	3,34 ± 1,77 µm	The particles have a spongy and rough structure, and the encapsulating matrix integrated homogeneously with nanovesicles of the oil.	-	-	Wheat gluten is effective in blocking oxidation for at least 10 days of exposure to UV light.	-	Porous solids facilitate absorption in the gastrointestinal tract.	(Prieto et al., 2021)
2	S	Algae oil	WPI:L 80%:20%	Spray drying	26 µm	Uniform size, smooth surface, and no clumps	98	-	The formation of protein-carbohydrate conjugates made the wall a barrier to oxygen, reducing hydroperoxides.	It is possible to transform an oxidizable liquid like oil rich in omega-3 fatty acids into a stable solid powder.	The surface area of the small oil droplets is large, therefore allowing pancreatic lipase to access oil molecules.	(Fu et al., 2020)
3	S	Algae oil	SC at 2% by weight SoA at 2% by weight Double coating (1) AO:SC = 1:9 (w/w) (2) 1: SC 1:1 (w/w) (3) 2: SoA 1:2 (w/w)	Electrostatic complexation	0.25 µm	The droplets of the emulsions were small, with a honeycomb structure, and they dispersed uniformly when the pH was adjusted from 7 to 5.	-	El ZP fue cambiando de -46,2 a -24,5 a medida que disminuía el pH	The anionic SoA is bound to cationic transition metals through electrostatic attraction, reducing the opportunity for contact with the oil.	-	After 2 hours, the digestion rate of SoA was 39.9 - 45.7. The lipid digestion rate depends on the surface exposed to lipase molecules.	(Ma et al., 2020)
4	S	Algae oil	T4:AO 50g:50g	Ultrasonic process	0.340 µm	The inclusion of Tween 40 may have reduced the droplet size range due to its lower molecular weight.	-	-	Lecithin is less stable to oxidation, particularly at higher temperatures.	The fatty acid composition showed no significant differences in temperature and storage.	-	(Lane et al., 2020)
5	S	Seaweed biomass (*Tetraselmis chuii*)	M:AG 60:40 20% solidos (w/v) + AB 1g/100mL	Spray drying	3.5 – 13.7 µm	The microcapsules presented a round, wrinkled shape with small holes.	-	-	Wall materials were found to cause stability during storage	-	-	(Bonilla-Ahumada et al., 2018)
6	S	Algae oil and phytosterol	AO (10% by weight)	Spray drying	158.2 nm	The AO powders were yellowish, fine and smooth, presented a continuous wall with no visible cracks on the surface of the particles	-	-	The incorporation of natural antioxidants, such as β-sitosterol and γ-oryzanol, preserve the oxidative stability of algal oil	The co-assembly molecules of sitosterol and oryzanol, form plate-like crystals in a network form, which preserves its stability	-	(Chen et al., 2016)
N	DB	Core	Formulation	Technique	Particle size	Morphology	EE %	ZP (mV)	Oxidation	Fatty acids	Digestibility	References
7	S	Algae oil	AO:T4 10%:2,8% (w/w)	Microfluidizer	0.148 µm	Non-ionic stabilized nanoemulsion beads (Tween-40) can provide better stability.	-	-34,50	The T4 emulsifier prevents physical stress imposed during emulsification on the central DHA algae oil.	The nanoemulsions showed no change in the fatty acid profile.	Digestibility was demonstrated in lipase that was hydrolyzed by the nanoemulsified lipids	(Karthik & Anandharamakrishnan, 2016)
8	S	Algae oil	AO:WPC:H_2O (w/w) Emulsion II: 1:0:4:16:23.8	Emulsion and Single Drop Drying Method	<20	Crust formation for emulsion-III took longer than the	-	-	-	-		(Wang et al., 2014c)

(*continued on next page*)

Table 3 (*continued*)

N	DB	Core	Formulation	Technique	Particle size	Morphology	EE %	ZP (mV)	Oxidation	Fatty acids	Digestibility	References
			Emulsin III:1:0:6:45.5			process for emulsion II.						
9	W	Algae oil *(Hizikia fusiforme)*	AO:G:SHX 40:300:300 g:g:g	Complex coacervation and freeze drying	200 – 3000 µm	Particles were yellow in color, fusiform in structure, irregular, but with smooth structure	-	-	Particulates can be enhanced by providing a nitrogen atmosphere to reduce lipid oxidation.	The microcapsules preserved linolenic, erucic, DHA, DPA, etc. fatty acids.	The particles conferred remarkable effects on memory in fish and rodents by elevating the cholinergic system and suppressing oxidative stress.	(Li et al., 2024)
10	W	Microalgae oil	Surfactants were used	Microfluidization	-	The particles were spherical and regular in shape	97 - 100	-22 a -30	The lipid carriers provided efficient encapsulation.	The fatty acids were stable at 4 and 25°C conditions.	-	(Wang et al., 2014b)
11	P	Algae oil	SL:T4 3%:3%	Ultrasonic	0.34 – 0.26 µm	-	-	-	-	As the nanoemulsion was directed into the duodenal phase, droplets disappeared and micelles of hydrolyzed fatty acids were formed, demonstrating a high rate of fatty acid digestibility.		(Zhou et al., 2024)
12	P	Microalgae oil	Cross-linked sodium caseinate (5% w/v) MD = 14.5%	Spray drying	-	The wall material forms a compact coating due to the covalent bonds of the crosslinker.	97	-	Cross-linking from 30 to 90 min demonstrated higher oxidative stability compared to longer times	-	Capsules exhibited sustained release of microalgae oil for 5 h	(Bao et al., 2011)

AO: algae oil, WG: wheat gluten, SC: sodium caseinate, SoA: sodium alginate, T4: tween 40, WPI: whey protein isolate, L: lactose, MD: maltodextrin, AG: gum arabic, AB: algae biomass, SP: saponin, G: gelatin, SHX: sodium hexametaphosphate, SL: lecithin, L: lactose, MD: maltodextrin, AG: gum arabic, AB: algae biomass, SP: saponin, G: gelatin, SHX: sodium hexametaphosphate, SL: lecithin; DB: Databases, S: Scopus, W: Web of science and P: Pubmed

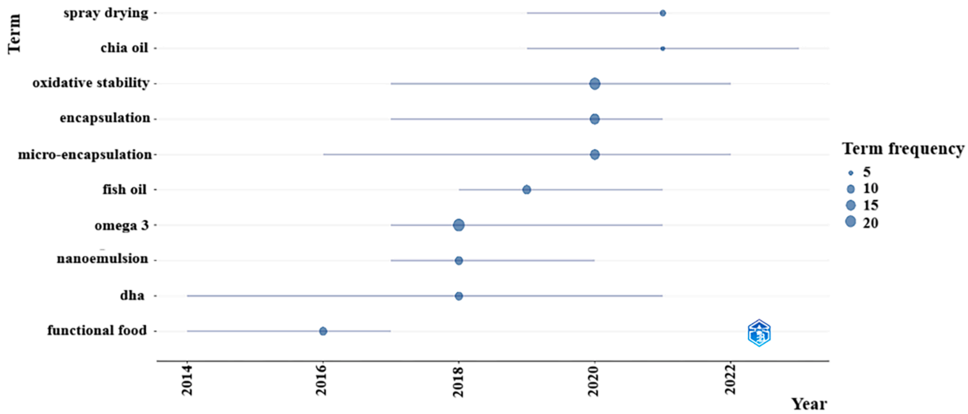

Fig. 7. Emerging thematic areas in omega-3 fatty acid microencapsulation research.

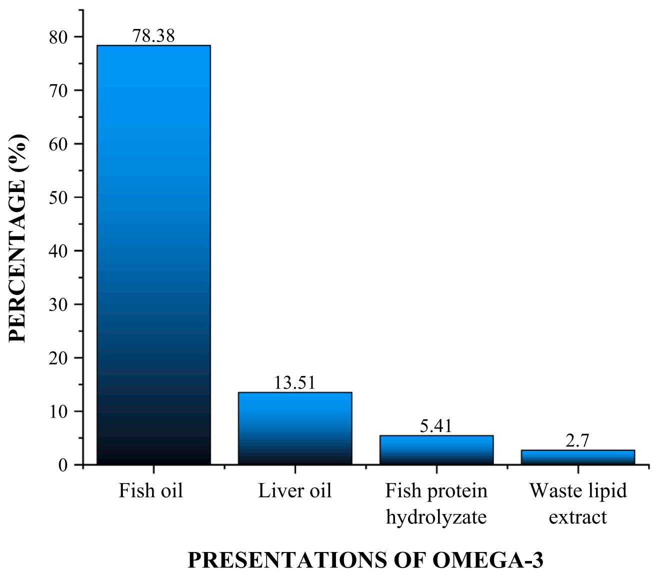

Fig. 8. Presentation of omega-3s of animal origin with the highest prevalence used for microencapsulation.

gelation. However, some studies have developed research approaches that combine both categories in order to preserve, protect, and extend the shelf life of the active compound, while improving the efficiency and functionality of the microcapsules (Espinoza-Espinoza et al., 2024). Fig. 9 details the most used methods for the microencapsulation of omega-3 derived from marine products.

3.2.1.3. Size and morphology. In the case of microcapsules loaded with fish oil, it was found that their morphology (size, shape, and structure) directly depend on various factors, such as the microencapsulation technique, lipid composition, emulsifier properties, and wall material. Intrinsic properties, such as the density and molecular weight of polyethyleneimine-glucose-modified starches, have been shown to produce nanoemulsions with long-term stability during storage. The binding of starch with PGU groups has the capacity to adsorb at the emulsion interface and effectively promote the formation of a protective network around the lipid core. This physical network disrupts instability processes such as coalescence and flocculation (Shehzad et al., 2021). On the other hand, optimizing the hydrophilic-lipophilic balance (HLB) at the emulsion interface plays a key role in determining the size and shape of microparticles. In the context, it was found that shrimp oil contains a significant number of phospholipids and therefore requires the use of polar emulsifiers with a high HLB value. This leads to the formation of small, homogeneous nanoemulsions. The use of emulsifiers such as Tween 80, which participates in molecular packing around the lipid core, has a positive impact on particle size and surface charge (Chaijan & Panpipat, 2019). Processes such as whey protein denaturation have been observed as a viable alternative for omega-3 protection, as they enhance interfacial adsorption and facilitate the formation of a less porous, protective surface layer (Eratte et al., 2016; Selim et al., 2021). Similary, zein has been shown to effectively coat fish oil,

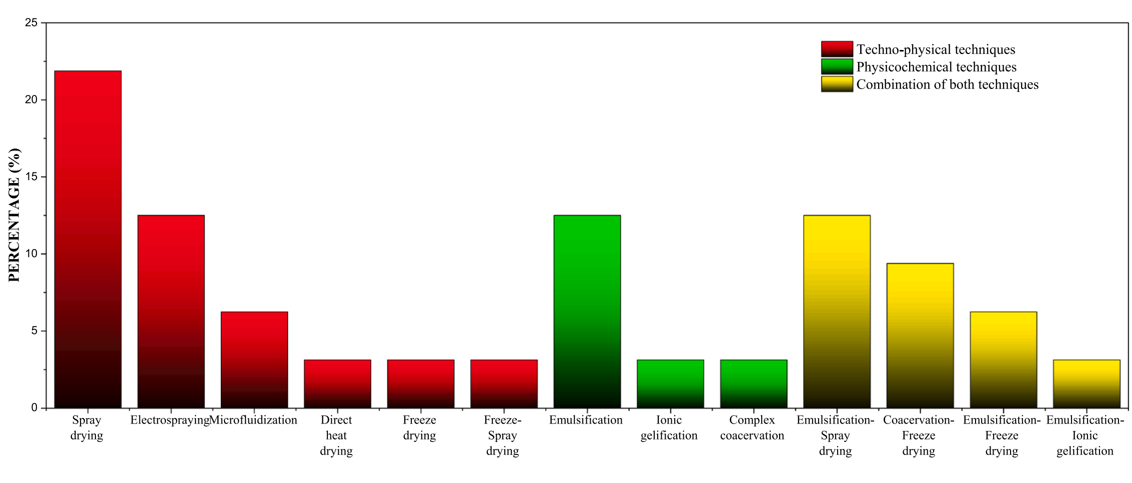

Fig. 9. Microencapsulation techniques are used in the protection of omega-3 from animal sources.

promoting the formation of spherical particles with uniform morphology. This is attributed to zein's intrinsic emulsifying capacity, which allows it to stabilize the emulsion prior to the encapsulation process and successfully entrap the oil within its matrix (Busolo et al., 2019). Finaly, certain technological processes directly influence the formation of these particles. Rahmani-Manglano et al. (2024) mention that, at a low spray drying temperature, water evaporation is slow and causes flexible particles during the encapsulation time, promoting rapid deromation.

3.2.1.4. Encapsulation efficiency. Encapsulation efficiency in fish oils is closely related to the behavior of the encapsulating material and the technique employed. As reported by Selim et al. (2021), protein denaturation has been identified as a favorable strategy compared to other materials such as gum Arabic and maltodextrin, achieving an encapsulation efficiency (EE) of up to 80% using spray drying. This efficiency is attributed to the emulsifying and chemical properties conferred by protein denaturation, which promote the stability of the encapsulated system. However, using the gelation technique with alginate and calcium chloride, divalent calcium ions are transferred into the emulsion, enabling the cross-linking of alginate chains and the subsequent formation of the encapsulating wall. This system achieved an encapsulation efficiency (EE) of 90% (Lamas & Álvarez, 2023). Shehzad et al. (2021) identified that EE is directly proportional to the particle size formed; that is, smaller particle sizes yield higher EE values. This theory is supported by Hasani et al. (2019), who argue that reducing the water content significantly decreases the diffusion coefficient of the lipid core compared to that in aqueous environments. During the drying process of the emulsion, water migrates from the matrix to the exterior at a significant rate, while the oil phase moves more slowly, remaining trapped within the wall material. This characteristic is essential, as the selected material exhibits semi-permeable properties that internal structure, reducing the available volume and promoting the formation of compact particles (Matos-Jr et al., 2017).

3.2.1.5. Oxidative stability. The oxidative stability of microcapsules loaded with fish oil is directly influenced by the encapsulation technique, the type of pf wall material, and the interaction between these factors. Each of these elements determines the degree of protection against oxygen transfer and interactions with conjugated diene compounds, thereby regulating the oxidation time of polyunsaturated fatty acids (Chang et al., 2021). Spray drying processes have been identified as more susceptible to oxidation; this instability may arise during the emulsification stage; although the emulsion is homogenized and immediately subjected to the drying process, operational variations (such as bubble formation) can facilitate oxygen ingress (Gómez-Guillén et al., 2023). However, the inclusion of proteins such as whey protein in drying processes has proven to be an effective agent, attributed to the early formation of a surface crust that limits oxygen transfer to the lipid core (Selim et al., 2021). This behavior is associated with thermal denaturation induced during drying, leading to the formation of a dense protein network with potential electrostatic and hydrophobic interactions that serve as a physical barrier against oxidation (Wang et al., 2022). Currently, emerging technologies such as coaxial electrospraying are being explored for the microencapsulation of fish oil as an alternative to conventional methods. This technique has shown a significant reduction in the formation of volatile compounds during storage, attributed to the localization of the lipid core at the center of a dense polymeric barrier that limits oxygen diffusion into the oil. Unlike spray drying systems, which form thin barriers with high surface areas that increase oxygen permeability, the coaxial structure achieves encapsulation efficiencies above 50%, demonstrating a greater lipid retention capacity.This efficiency is attributed to the absence of an emulsification stage and temperature increase, which limits oxygen incorporation and reduces free radical formation, contributing to a lower rate of lipid peroxidation (Rahmani-Manglano et al., 2024). On the other hand, the formation of microcapsules through chemical methods such as complex coacervation has proven to be highly dependent on the physicochemical characteristics of the lipid phase. Emulsions formulated with acylglycerols and coated with gelation and sodium hexametaphosphate under acidic conditions were strongly influenced by electrostatic forces and hydrophobic interactions, resulting in higher coacervation yields and compact microparticles. In contrast, microcapsules loaded with tuna oil exhibited smoother and more heterogeneous morphologies; systems loaded with acylglycerols showed a higher aggregation capacity due to surface hydrophobicity, lower apparent viscosity, low zeta potential, and other factors that intensified coacervation behavior (Xuan et al., 2023). These findings, form a chemical standpoint, indicate that the strength of molecular interactions among components in the emulsifying system is a critical factor in the formation of denser capsule barriers, which favors higher encapsulation efficiency of lipid compounds (Eratte et al., 2014). From a technological perspective, they highlight the importance of controlling capsule microstructure and optimizing processing parameters as effective strategies to minimize lipid oxidation in oils. Finally, the use of natural antioxidants, such as rosemary extract and y δ-tocopherol, has proven effective in enhancing the oxidative stability of microcapsules by reducing the formation of peroxides and other oxidative degradation products, thereby extending the shelf life of encapsulated omega-3 compared to systems without added antioxidants. However, this effect is dose-dependent, as there is evidence that excessive antioxidant levels may promote pro-oxidation (García-Moreno et al., 2017)

3.2.1.6. Fatty acid profile. While microencapsulation is considered an effective tool for protecting various excipients, its true success is achieved only after a thorough characterization of the encapsulated core. The complete preservation of the excipient through each stage is crucial, as any functional or structural alteration would compromise the quality of the final product. At this point, the evaluation of the fatty acid profile becomes particularly relevant, as it allows for the determination of whether the microencapsulation process has fulfilled its intended purpose. In this regard, from a chemical perspective, it has been identified that different coating materials exhibit variations in fatty acid preservation. Microcapsules made with whey protein and inulin retain higher proportions of MUFA and PUFA compared to those formulated with fucoidan. These characteristics are largely attributed to the effect of particle surface charge on lipid oxidation. In systems where anionic polymers such as fucoidan and inulin are combined, a higher negative charge is achieved, which increases the particles' ability to attract pro-oxidant metal cations to the surface. This attraction can accelerate fatty acid degradation through Fenton-type catalytic reactions (Jamshidi et al., 2018). Meanwhile, when there is a balance of surface charges, complex formation is favored specifically between gum Arabic (negative charge) and whey protein (positive charge). This balance is evidenced by a higher degree of molecular maturity, where turbidity reflects an increase in interfacial charge density and particle aggregation, resulting from the electrostatic interaction between biopolymers. This interaction produces a dense and soft phase composed of biopolymers that promote the formation and stability of coacervates. This effect minimizes the exposure of unsaturated fatty acids to oxidative factors (Eratte et al., 2014; Habibi et al., 2017). It is essential that this balance undergoes an optimization process, as an excess or deficiency of coating materials can lead to soluble and structurally altered microcapsules. Therefore, from a chemical standpoint, the modulation or surface charge and the selection of wall materials not only affect the structural stability of the particles but also the chemical stability of the lipid core. This highlights the importance of designing strategic encapsulating systems to minimize lipid oxidation and preserve the nutritional quality of the encapsulated oil (Chaijan & Panpipat, 2019)

3.2.2. Omega-3 encapsulation using plant sources

The utilization of plant-based resources has gained significant importance in the recovery and use of bioactive compounds with high functional and nutritional value. Among these compounds, plant-derived fatty acids stand out for their various health benefits in the human body; however, in their natural state, these compounds are embedded within lipid matrices or structurally bound, which limits their bioavailability and physiological utilization. These factors have driven the search for extraction and protection methods that enable efficient recovery while preserving their chemical integrity against degradation factors. In the present research, 16 plant varieties have been identified for the microencapsulation of omega-3, including: *Glycine max, Brassica napus, Salvia hispanica, Helianthus annuus, Linum usitatissimum, Plukenetia volubilis, Olea europaea, Echium vulgare, Juglans regia, Phaseolus vulgaris, Hibiscus cannabinus, Peonia arborea, Cuminum cyminum, Triticum,* and *Cannabis* (Alfaro-Rodríguez et al., 2022; Bordón et al., 2023).

3.2.2.1. Core or source of encapsulation. The plant sources identified in this review include 16 varieties, among which Flaxseed, Chia, and Sacha Inchi oils stood out due to their higher frequency of use in omega-3 fatty acid microencapsulation processes (Fig. 10). This trend can be attributed to their high contents of linoleic and α-linolenic acids, which account for approximately 51% and 57% of their total fatty acids, respectively (Chasquibol et al., 2023; Dabiri Movahed et al., 2024). However, due to their high degree of unsaturation, these compounds are susceptible to oxidation processes, promoting the formation of undesirable compounds and limiting their nutritional value (F. Chen, Liang, et al., 2017). Therefore, their protection is essential to preserve their structural integrity and bioactivity in food applications.

3.2.2.2. Encapsulation technique. The encapsulation techniques identified for the microencapsulation of plant-based omega-3 included both techno-physical and physicochemical processes, as well as the combination of both categories. As shown in Fig. 11, spray drying is the most used technique. This preference may stem from several factors, such as its high efficiency, industrial scalability, and compatibility with sensitive compounds like polyunsaturated fatty acids (Chasquibol et al., 2023; Kanwal et al., 2021; Shahid et al., 2020). However, it is also possible that the frequent use of spray drying is not solely due to its efficiency and versatility with a wide range of excipients, but also to the researcher's criteria, who may see these techniques as offering strong potential for optimization and adjustment to improve oxidative stability and encapsulation efficiency of omega-3 fatty acids.

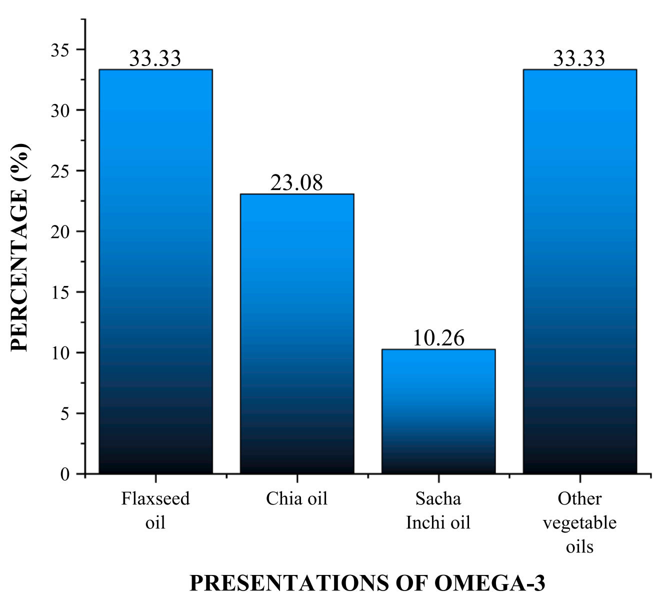

Fig. 10. Presentation of omega-3s of plant origin with the highest prevalence used for microencapsulation.

3.2.2.3. Size and morphology. The morphological behavior of plant-based microcapsules was identical to that of animal-based ones, as the particles were influenced by the concentrations of the coating material. Particles coated with *Prunus armeniaca gum* (PAGE) produced smaller microparticles due to weaker interactions between functional groups; however, when the PAGE/Chitosan ratio was optimized, both the size of the microparticles and the interactions among functional groups increased (Dabiri Movahed et al., 2024). A similar behavior was observed in hydrogel beads produced in the presence of sodium caseinate, where the incorporation of this protein significantly increased the size of the beads compared to those formulated without caseinate. This phenomenon is attributed to the rapid cross-linking induced by Ca^{2+} ions on the surface of the droplets, which favors the formation of spheres with uniform and smooth surfaces, possibly due to a high density of cross-links at the interface (Chen, Liang, et al., 2017). A relevant finding is that the sphericity and laminar structure of the microcapsules significantly contribute to improving the physical stability of the system by reducing the risk of particle aggregation (Bhushan et al., 2017). Morphologically, the presence of cracks, dents, or imperfections on the surface of microparticles can lead to noticeable adverse effects, such as surface discoloration; for example, the transition from white to yellow may indicate flocculation and/or coalescence processes in encapsulated Flaxseed oil (Cheng et al., 2019), Therefore, one alternative is the combination of polysaccharides and proteins in the microcapsule wall, which has proven effective in creating stable structures and preventing recoalescence of oil droplets (Abbasi et al., 2019; Julio et al., 2019)

3.2.2.4. Encapsulation efficiency. The microencapsulation efficiency of plant-based omega-3 was directly influenced by operational parameters such as temperature. In particular, the use of polysaccharide gum derived from Flaxseed flour as the wall material achieved an encapsulation efficiency of 90.78% at 160°C. This temperature, higher than the evaluated 120°C and 140°C, promoted faster microparticle formation and a more stable coating, which helped minimize oil migration to the exterior (Shahid et al., 2020). This theory was supported by Rodríguez-Cortina & Hernández-Carrión, (2023), who reported that a temperature of 170°C resulted in an acceptable efficiency of 70%; however, they also noted that using excessively high temperatures leads to severe evaporation and results in cracked microparticles, which could cause premature oxidation. On the other hand, the efficiency of WPC as a wall material for the protection of lipid cores continues to be evident; under thermal denaturation conditions between 77°C and 86°C, the ternary combination of WPC, SPI, and GA in an 8:1:1 ratio resulted in stable microparticles with an encapsulation efficiency of 79.88%. This formulation appears promising for incorporation into food matrices (Bordón et al., 2023). Finally, not only did WPI demonstrate high efficiency in the microencapsulation of lipid cores, but it also proved effective in complex systems such as mixtures of Sacha Inchi oil with antioxidant extracts. This behavior is attributed to the ability of proteins to modify the interfacial properties of emulsions, reduce surface tension, and promote efficient interaction between the core and the wall material, achieving encapsulation efficiencies above 80% (Chasquibol et al., 2023).

3.2.2.5. Oxidative stability. Oxidative stability is a key factor that must be prioritized in all systems containing lipid cores. For example, Flaxseed oil contains a high amount of polyunsaturated fatty acids (PUFAs), making it essential to develop a stable and effective coating, as the primary oxidation products although not causing perceptible changes in odor are highly toxic for human consumption (Kanwal et al., 2021). A promising approach is the inclusion of natural antioxidants, such as quercetin, which has shown a significant reduction in lipid oxidation

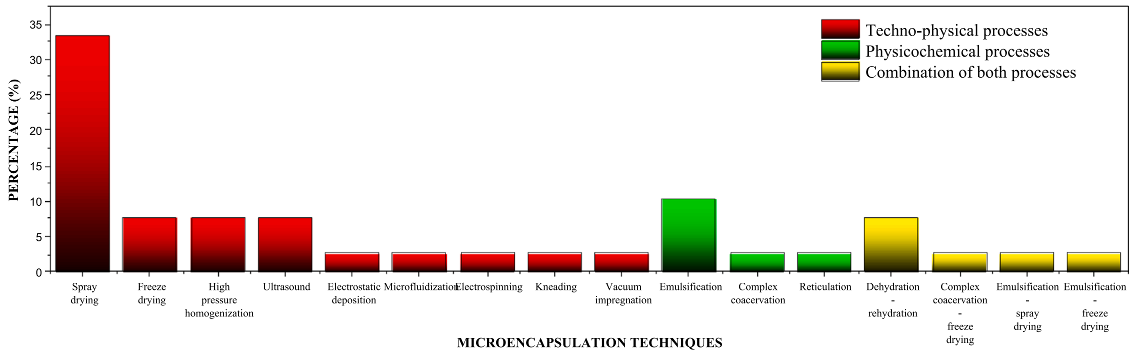

Fig. 11. Microencapsulation techniques are used in the protection of omega-3 from plant sources.

and an extension of the product's shelf life. This flavonol belongs to the group of polyphenols and contains multiple hydroxyl groups that provide it with a high capacity to neutralize free radicals. Its incorporation into Flaxseed oil has proven effective in delaying oxidative processes and preserving the integrity of the encapsulated system (Huang et al., 2017). In addition to polyphenols, compounds such as ascorbyl palmitate have significantly influenced the oxidative stability of vegetable oil's its incorporation into microencapsulated chia oil has helped maintain low oxidation levels during storage, demonstrating that antioxidants enhance the efficiency and stability of the system (Ixtaina et al., 2022). This behavior was also observed with sinapic acid in combinations with gelation and gum Arabic, whose incorporation increased the oxidative stability of Echium oil up to 10 times compared to pure Echium oil (Comunian et al., 2017). One of the key characteristics for achieving good stability in microparticles loaded with lipid cores is the formation of β'polymorphs; that is, lipid coatings can rearrange without altering their chemical composition. This typically occurs when lipid-based materials are used as coating agents (Espinoza-Espinoza et al., 2024). Coating made from WPI and lauric acid have been shown to form compact and stable polymorphic structures capable of significantly reducing the diffusion rate of pro-oxidant metals and oxygen. Additionally, the fatty acids present in Echium oil exhibited grater affinity to bind to a crystalline network of lipid coatings when slow cooling was applied, compared to rapid cooling, thus promoting a more ordered and oxidation-resistant structure (Azizi et al., 2018). Finally, the presence of polar lipids and proteins in the encapsulating system enables the formation of viscoelastic coating at the oil/water interface; these hydrophobic interactions, combined with electrostatic and steric repulsions, stabilize emulsions and limit coalescence. This synergistic interaction strengthens the interfacial structure and enhances resistance to adverse storage conditions (Aghababaei et al., 2021)

3.2.2.6. Fatty acid profile. As previously mentioned, one of the main indicators of effective microencapsulation is its ability to preserve the nutritional and functional quality of the lipid core in its original state, thereby extending its shelf life and stability during processing, storage, and final use in food systems. This desired stability is the result of various factors involved in the microencapsulation process, such as the incorporation of antioxidant compounds that delay the onset of primary and secondary oxidation. At the intrinsic level, the preservation of the nutritional and functional quality of plant-based omega-3 can be compromised during the formation of the coating walls, as these walls are composed of electrostatic and/or synergistic interactions, whose intensity can vary with factors such as pH. These variations can lead to dense microparticles capable of providing greater oxidative stability to the encapsulated oil (Dabiri Movahed et al., 2024). In studies with Flaxseed oil, ultrasound-assisted nanoemulsions were able to maintain a stable fatty acid profile for 30 days, reflecting high encapsulation efficiency and antioxidant protection (Abbasi et al., 2019). This behavior is attributed to the formation of nanoemulsions stabilized by polysaccharide-protein complexes, such as SoA and WPI, which exhibit a highly negative charge. This charge indicates the presence of stable bilayers around the particles, formed by electrostatic interactions between anionic components, thereby promoting greater system stability and preventing particle coalescence. These results highlight the potential of plant-based sources not only to preserve the integrity of fatty acids during storage but also to improve their bioavailability, especially in acidic food matrices such as yogurts of fortified juices (Kanwal et al., 2021).

3.2.3. *Omega-3 encapsulation using protist sources*

The utilization of resources from the Protista kingdom, such as micro and macroalgae, has gained increasing attention due to their ability to synthesize compounds with high nutritional and functional value. Among these, omega-3 polyunsaturated fatty acids, such as DHA and EPA, stand out for their well-known benefits to human health (Fu et al., 2020). These algae, which commonly grow naturally attached to rocky surface, docks, or boat hulls, are often considered biological waste. Therefore, their use can be seen as an environmental and sustainable strategy, providing alternative sources of omega-3 without relying exclusively on traditional marine resources such as fish oil.

3.2.3.1. Core or source of encapsulation. This review has identified the use of oils extracted from both commercial micro and macroalgae as well as specific species such as *Tetraselmis chuii* and *Hizikia fusiforme,* with the aim of protecting and preserving the stability of omega-3 fatty acids against oxidative processes. As previously described, these compounds are highly susceptible to oxidative degradation, which compromises their functionality and safety in food systems. A total of 12 scientific articles were reviewed, addressing various encapsulation strategies aimed at preserving the integrity of these lipids and extending their shelf life during storage.

3.2.3.2. Encapsulation technique. The microencapsulation of polyunsaturated amega-3 fatty acids whether from animal, plant, or protist sources has proven to be an effective strategy for preserving their nutritional quality, extending their shelf life, and facilitating their incorporation into food systems. While spray drying is one of the most widely used techniques due to its scalability, low cost, and efficiency, recent studies involving protist sources such as algae have incorporated innovative methods like microfluidization and electrospraying (Fig. 12) to optimize nanoemulsion formation and improve intestinal absorption (Prieto et al., 2021). Collectively, these developments reflect an evolution toward efficient and sustainable processes tailored to the specific characteristics of each type of omega-3, highlighting the key role of microencapsulation as a crucial tool in the development of next-generation functional ingredients.

3.2.3.3. Size and morphology. The use of different coating materials, such as wheat gluten applied to algal oil, has resulted in microparticles

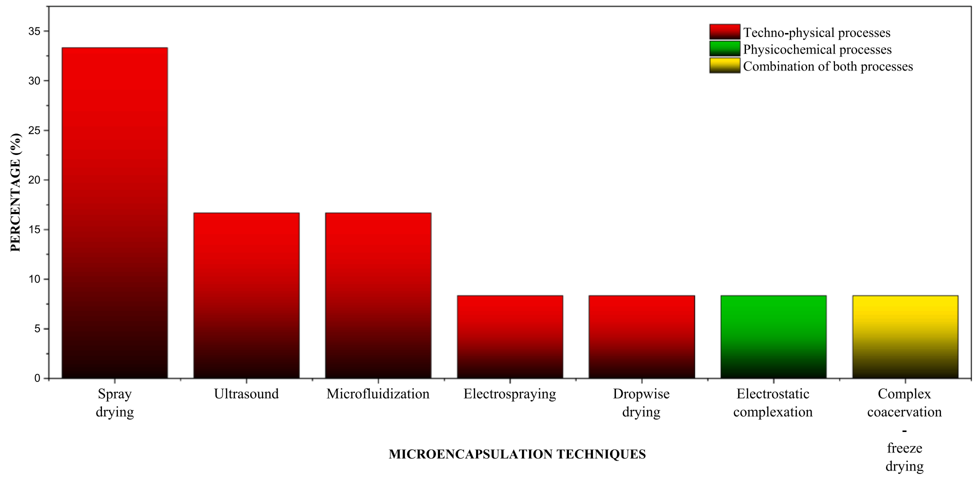

Fig. 12. Microencapsulation techniques are used in the protection of omega-3 from protist sources.

with reduced size and rough morphology. According to Prieto et al. (2021), these characteristics may be influenced by the physicochemical properties of the solution, such as surface tension, viscosity, and conductivity. Although smaller microparticles offer technological advantages such as lower impact on food texture and better dispersibility, their high surface-to-volume ratio increases lipid exposure to pro-oxidant agents, which could compromise oxidative stability. On the other hand, the agglomeration observed in some microparticles is attributed to partial adhesion between the coating materials. As previously documented, extreme processing conditions lead to protein denaturation, which slows the formation of a uniform coating and promotes surface coalescence of the particle; this has been observed in the use of WPI and GS. However, when sodium starch octenylsuccinate was used, a smooth, dense, homogeneous, and non-agglomerated surface was observed, highlighting its efficiency as an encapsulation system for preserving the integrity of polyunsaturated lipids (Fu et al., 2020).

3.2.3.4. Encapsulation efficiency. A significant efficiency of DHA identified in microencapsulation systems is promoted by the composition of lipid carries in both solid and liquid states; this combination enables the formation of coatings with structural imperfections. Such structural alteration is one of the key features that prevents the formation of homogeneous crystals during cooling and oil stabilization, generating voids within the structural network that facilitate the incorporation of polyunsaturated fatty acids (Bao et al., 2011; Wang et al., 2014b). Materials such as lipid carries and natural polymers, due to their structural versatility, can effectively retain protist-derived omega-3. However, variables such as extreme temperatures or carrier ratios may compromise this efficiency, highlighting the need for rigorous control of formulation parameters to preserve the quality of the microencapsulated lipid core.

3.2.3.5. Oxidative stability. Lipid oxidation is an interfacial process that preferably beings at the interface of the microparticles, where polar and non-polar compounds of the emulsion interact. In this context, surfactants such as β-sitosterol have gained considerable interest in microencapsulation, as they efficiently embed themselves at the oil/water interface, form a dense layer over the lipid droplet, and act as a barrier against the penetration of oxidizing agents (Chen et al., 2016). This protection is attributed to the intrinsic antioxidant capacity of β-sitosterol and its ferulated phytosterol structure, which stabilizes the lipid core and blocks free radical chain reactions. This prevents the formation of hydroperoxides and other volatile primary oxidation products responsible for unpleasant odors commonly described as "fishy". From the perspective of oxidative stability, the combination of sodium caseinate and sodium alginate has proven particularly effective, acting as a protective barrier against oxygen. This significantly improves the stability of omega-3 fatty acids against oxidation, even under prolonged storage conditions or exposure to ultraviolet light (Ma et al., 2020)

3.2.3.6. Fatty acid profile. Microencapsulation processes applied to omega-3 fatty acids of protist origin, primarily extracted from micro and macroalgae, have shown a high capacity to preserve their functional and structural quality. These oils, rich in polyunsaturated fatty acids such as DHA, DPA, erucic, and linolenic acids, were successfully transformed from an unstable liquid phase into a solid microencapsulated form protecting them against oxidation and improving their technological manageability (Li et al., 2024). The studies reviewed indicated that processing temperature and time did not significantly affect the fatty acid composition, suggesting high thermal resistance when process is under controlled conditions. Finally, it was found that the microparticles maintained their integrity under storage conditions at 4°C and 25°C, confirming their effectiveness as an oxidative barrier (Wang et al., 2014a).

3.2.4. Foods fortified with omega-3 microcapsules

The fortification of foods with microencapsulated omega-3 fatty acids has shown significant advancements in the food industry, enabling the incorporation of lipid cores into polymeric matrices without compromising sensory quality or product stability. Currently, instant foods have been developed using undervalued fish meat pieces enriched with fish oil microencapsulated in k-carrageenan and protein hydrolysates via spray drying; this approach not only improves texture and binding capacity but also preserves significant amounts of omega-3 fatty acids (EPA and DHA), while promoting fishery sustainability through the utilization of marine by products (Gómez-Guillén et al., 2023).

On the other hand, it has been shown that microencapsulation systems composed of gelled lipid carriers efficiently protected cuminaldehyde against adverse environmental conditions such as temperature, ionic strength, and pH. These systems delay oxidation and promote antimicrobial effects, suggesting their suitability for use in functional foods (Ghiasi et al., 2021). The direct incorporation of omega-3 microcapsules into bakery products altered their physical characteristics, such as firmness, volume, and color, but not their sensory acceptability. Furthermore, the inclusion of natural antioxidant extracts did not negatively affect the technological or sensory qualities, demonstrating the feasibility of using antioxidants to prevent lipid oxidation without compromising product quality (Costa de Conto et al., 2012). Similarly, Flaxseed oil was microencapsulated in a ternary matrix and incorporated into bread samples. In this case, the visual characteristics were similar to the control; however, a minimal percentage of α-linolenic acid degradation was observed after baking (Gallardo et al., 2013). Finaly, in the dairy sector, the incorporation of microencapsulated fish oil improved the physicochemical properties of yogurt, such as water retention, apparent viscosity, and acidity. During storage, the microcapsules protected the oil from oxidation, resulting in a lower peroxide rate without negatively affecting the sensory perception of the panelists, compared to free oil (Tamjidi et al., 2012). These results confirm that microencapsulation not only stabilizes polyunsaturated fatty acids against technological processes and storage conditions but is also compatible with different types of food systems and formulation strategies, supporting the development of functional foods fortified with omega-3 from animal, plant, and protist origins.

4. Conclusions

Through bibliometric analysis, this study identified a growing trend in omega-3 microencapsulation research over the past decade, highlighting the consolidation of international networks, the interest in preserving oxidative stability, and the formulation of functional matrices. The microencapsulation efficiency of omega-3 fatty acids largely depends on the oiĺs origin and the chemical interactions between the wall material and lipid core. Animal derived oils, rich in DHA and EPA, exhibit high oxidative susceptibility, requiring protein-based matrices and multilayer systems capable of forming dense, cohesive coatings that reduce oxygen permeability. In contrast, vegetable oils such as Chía, Sacha Inchi, and flaxseed are dominated by α-linolenic acid and demons that greater oxidative resistance, though they still require emulsifying materials to maintain nutritional quality, functionality, and controlled release.

Meanwhile, oils from protist sources particularly microalgae offer additional advantages by promoting the formulation of stable and highly digestible nanostructures, positioning them as promising compounds for next generation functional foods. The stability of the encapsulation systems identified in this review is attributed to the formation of electrostatic bonds and hydrophobic interactions between polysaccharides and proteins, which impart structural rigidity and resistance under thermal of storage conditions. The controlled distribution of oil within the solid matrix limits the migration of oxidizing compounds and radical mobility, thereby preserving the original fatty acid profile. The compiled results demonstrate the potential of these technologies for the development of fortified, functional foods with controlled release. Future research should focus on the rational design of hybrid materials, the integration of natural antioxidants, and the incorporation of emerging tools such as artificial intelligence and nanotechnology to optimize the efficiency, sustainability, and stability of omega-3 encapsulation systems.

Data availability statement

The data generated, analyzed, and obtained in this study will be provided by the authors without undue reservation.

Ethical statement - studies in humans and animals

The authors declare that no experiments were conducted on humans or animals in this research.

CRediT authorship contribution statement

William Vera: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Henry Daniel Muñoz-More:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Luis Alberto Ruiz-Flores:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Juliana Maricielo Nole-Jaramillo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Diana María Nolazco-Cama:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luis Alfredo Espinoza-Espinoza:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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