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Marine lipids: A review of sources, extraction methods, characterization, and food applications

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ABSTRACT

This comprehensive review examines sources, extraction methods, biochemical characterization, and biotechnological applications of marine lipids, with particular emphasis on omega-3 polyunsaturated fatty acids (PUFAs) including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). This study presents the diverse lipid compositions across marine organisms, from simple fatty acids to complex phospholipids, glycolipids, and sterols, according to the LIPID MAPS classification. Advanced extraction and analytical techniques including supercritical fluid extraction, gas chromatography-mass spectrometry (GC-MS), and liquid chromatography-electrospray ionization tandem mass spectrometry (LC-ESI-MS/MS) are critically evaluated for their efficiency in marine lipid isolation and characterization. The health benefits of marine lipids are extensively documented, demonstrating significant anti-inflammatory, cardiovascular protective, hepatoprotective, and neuroprotective properties through various molecular mechanisms. Biotechnological applications span across nutraceuticals, pharmaceuticals, cosmetics, and sustainable industrial processes, with marine lipids showing particular promise in the development of functional foods. Current challenges including sustainability concerns, climate change impacts on marine ecosystems, and scalability of production are addressed alongside future perspectives for technological innovations in extraction methods, encapsulation technologies, and food integration strategies. This review underscores the critical importance of marine lipids as sustainable alternatives to conventional sources while highlighting their potential to address global nutritional challenges and support the development of next-generation health-promoting products.

1. Introduction

Marine organisms are a rich source of bioactive compounds with unique biochemical and functional characteristics. These compounds, particularly lipids, play a vital role in enabling marine species to adapt to fluctuating environmental conditions such as temperature, salinity, pH, and light. Among these, lipids are key structural and metabolic components that contribute significantly to membrane fluidity, energy storage, and cellular signalling. Owing to the complex marine environment, marine lipids often exhibit highly diverse chemical compositions, sometimes containing more than 50 distinct fatty acids, including sterols, waxes, sterol esters, and phospholipids (Pateiro et al., 2022).

Essential fatty acids such as α-linolenic acid (ALA, C18:3n-3) and linoleic acid (LA, C18:2n-6) are indispensable to humans and animals, as they cannot be synthesized endogenously and must be obtained through diet. Long-chain omega-3 polyunsaturated fatty acids (LCPUFAs), particularly eicosapentaenoic acid (EPA, C20:5n-3), docosapentaenoic acid (DPA, C22:5n-3), and docosahexaenoic acid (DHA, C22:6n-3), are derived from these precursors and are crucial for maintaining physiological balance and promoting human health. Variations in lipid profiles across marine species are influenced by factors such as age, sex, species type, diet, habitat, and environmental temperature. There is a wide

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spectrum of fatty acids among marine life; certain species show long-chain fatty acids (Pateiro et al., 2021). A range of biological and environmental variables such as species, age, size, sex, seasonality, and temperature affect lipid composition.

In recent decades, marine lipids have attracted growing scientific and commercial interest due to their nutritional and therapeutic potential. Extensive research has demonstrated the benefits of omega-3 fatty acids in reducing inflammation, supporting cardiovascular function, enhancing brain development, and mitigating metabolic and immune-related disorders. Consequently, seafood and marine-derived products have been recognized as key natural sources of health-promoting lipids that align with global public health goals aimed at reducing lifestyle-related diseases. (Oliver, Dietrich, Marañón, Villarán, & Barrio, 2020). Recent research has shown that microalgae, krill, and certain shellfish can serve as alternative and sustainable sources of long-chain omega-3 polyunsaturated fatty acids (LCPUFAs), reducing dependency on traditional fish oils (Oliver et al., 2020; Pham et al., 2024).

In the last five years, marine lipid research has evolved rapidly, driven by advances in lipidomics, green extraction technologies, and biotechnological production systems. Techniques such as supercritical CO_2 extraction, enzymatic hydrolysis, and microwave-assisted extraction have improved lipid recovery efficiency while minimizing oxidative degradation and environmental impact (Imamoglu, 2024; Mishra et al., 2025). Concurrently, lipidomics and high-resolution mass spectrometry (LC-ESI-MS/MS, HRMS) have enabled comprehensive profiling of complex lipid classes, including phospholipids, glycolipids, and sulfolipids, enhancing understanding of their bioactivity and nutritional relevance (Rey et al., 2022).

The application spectrum of marine lipids has also broadened. Recent developments highlight their potential in functional foods, pharmaceutical formulations, and cosmeceutical products, reflecting growing industrial and consumer demand for natural bioactives with health-promoting properties (Prates, 2025). Moreover, the sustainability aspect of marine lipid sourcing has become a central research focus. Studies on algal cultivation, aquaculture by-product utilization, and circular bioeconomy models aim to ensure the long-term availability of marine lipids while preserving oceanic ecosystems (Veríssimo et al., 2021).

The biotechnological exploration of marine lipids has expanded beyond nutrition to include their applications in pharmaceuticals, cosmetics, and functional foods. Efficient utilization of marine resources for lipid extraction not only provides high-quality bioactive compounds but also promotes sustainability through innovative processing and value addition. Harnessing these lipids presents new opportunities to develop nutraceutical and therapeutic products, contributing to improved human health and sustainable use of marine biodiversity.

Despite extensive studies on marine-derived lipids, there remain critical gaps in integrating recent technological advancements, sustainability considerations, and functional applications into a unified perspective. Most existing reviews have focused either on biochemical aspects or extraction techniques, with limited emphasis on linking lipid diversity to biotechnological and industrial utilization. Furthermore, there is a pressing need to consolidate emerging evidence from lipidomics, green extraction technologies, and novel marine resources to promote sustainable exploitation of marine bioactives.

Unlike earlier reviews that primarily provide a broad overview of marine lipids and omega-3 fatty acids, this study offers a focused synthesis of recent advances in marine lipid science. It emphasizes innovative green extraction and encapsulation techniques, lipidomic-based characterization, and sustainability challenges unique to marine resources. Particular attention is given to non-conventional sources such as microalgae, krill, and shellfish, highlighting their biochemical potential and environmental advantages. By integrating current technological progress with sustainability and nutritional perspectives, this review presents an updated and specialized understanding of marine lipids in the context of modern food and biotechnological applications.

2. Methodology

This review followed a structured process to ensure scientific rigor and relevance. A comprehensive search was carried out across Scopus, PubMed, Web of Science, Google Scholar, Springer Link, and Wiley Online Library using Boolean combinations of terms related to marine lipids, omega three fatty acids, lipidomics, extraction methods, and marine bioactives. The search covered publications from 2014 to 2025 and yielded an initial pool of 1586 articles. After duplicate removal and title and abstract screening, studies were assessed through full text evaluation based on predefined criteria: peer reviewed publications reporting original data or detailed reviews on marine lipid composition, extraction, characterization, or applications. Non English papers, conference abstracts, book chapters, and theses were excluded. Following this process, 284 articles met the inclusion criteria. These were grouped into thematic categories covering lipid sources, extraction and purification technologies, biochemical and structural analysis, and health and industrial applications. Data extraction focused on methodological clarity, lipid class detail, and analytical approaches. To support trend analysis, bibliometric mapping using VOSviewer version 1.6.20 was performed to visualize keyword co-occurrence, co authorship, and citation patterns Figs. 1 and 2.

3. Sources and organisms

Marine organisms represent a diverse and sustainable reservoir of lipids with unique structural and functional properties. These lipids, particularly polyunsaturated fatty acids (PUFAs) such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), occur across multiple marine taxa, including fish, shellfish, crustaceans, krill, and algae (Table 1). The lipid composition and yield vary considerably among species and are influenced by environmental factors such as temperature, depth, and nutrient availability. Understanding these biological and ecological variations is essential for identifying optimal sources and developing efficient extraction strategies for industrial and nutraceutical applications

3.1. Fish

Fish is considered to be one of the most nutritive foods of animal origin, due to the high protein content, balance of essential amino acids, and high levels of fat-soluble vitamins it contains, as well as vital macro- and microminerals (Al Khawli et al., 2019). The proximate composition typically ranges from 0 % to 25 % lipids, 15–30 % proteins and 50–80 % moisture. This composition is influenced by various factors such as size, age, fish species, seasonal variations, available feed, habitat temperature, and gender, among others (Shavandi, Hou, Carne, McConnell, & Bekhit, 2019). In this context, whitefish species such as cod and hake are classified as lean species, comprising 20 % protein, 80 % water, and relatively low lipid levels ranging from 0.5 % to 3 %. Conversely, fatty fish such as Mackerel and salmon exhibit elevated lipid levels (10 %–18 %) and reduced water content (62 %–70 %). Furthermore, the fatty species exhibit elevated concentrations of n-3 LCPUFAs. In this context, the lipid contents reported for swordfish, eel, halibut and salmon were 20.4, 13.5, 12.4, and 11.7 g per 100 g of fresh edible portion, respectively. Furthermore, the surroundings where they reside affect the fatty acid composition. Consequently, pelagic species exhibit greater levels of PUFAs compared to demersal species. Tuna, salmon, sardine, and mackerel would validate the assertion. Furthermore, organisms cultivated in colder aquatic environments typically exhibit elevated levels of these fatty acids (Ahmad, Rudd, Kotiw, Liu, & Benkendorff, 2019). Despite this, there have been controversy surrounding this statement. According to a meta-analysis of factors including phylogeny (order identity), feeding type (trophic level), habitat (marine or freshwater),

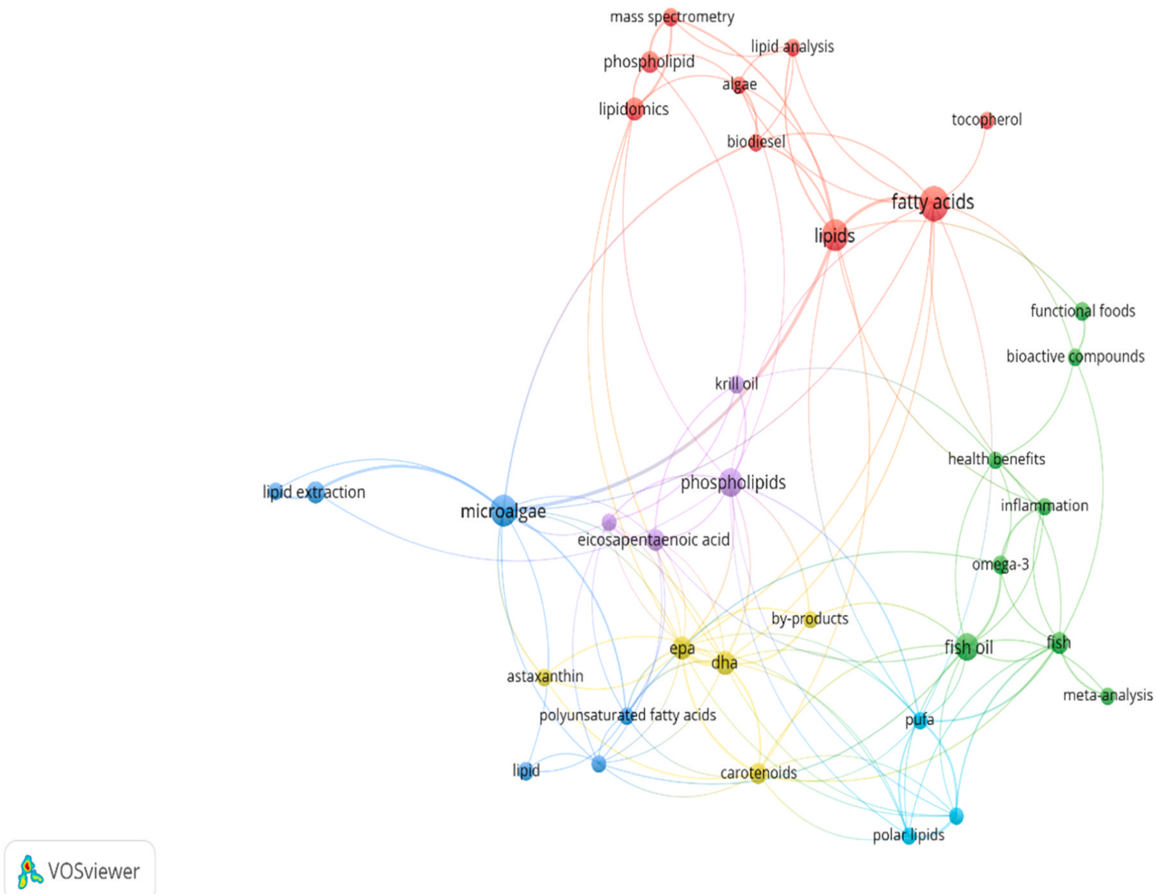


Fig. 1. Keyword network illustrating the relationships among different aspects of lipid research, from extraction to health benefits.

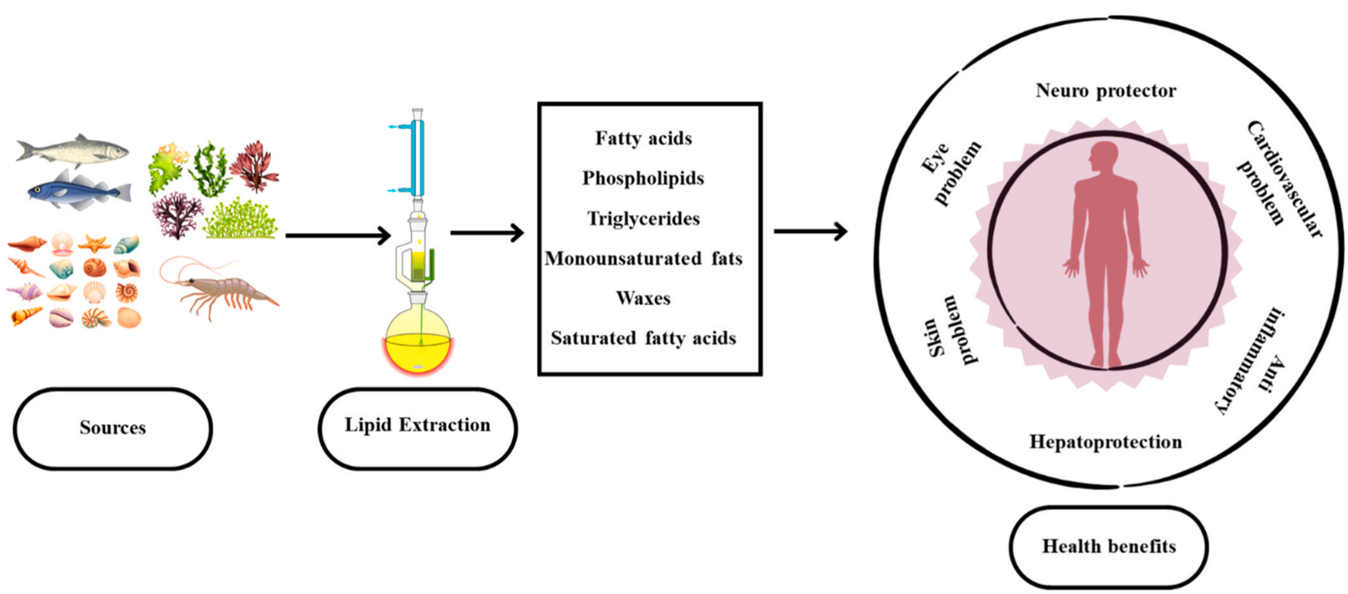


Fig. 2. Extraction of lipids from marine organisms and their potential health benefits.

size, and movement, a combination of phylogenetics and eco-morphology is responsible for the variation in EPA and DHA levels between species. In addition, several authors claim that species' high FA concentrations are due to adaptations to specific lifestyles in specific environments (Pateiro et al., 2022). In this context, fast swimming marine planktivorous organisms, which rely on planktonic food sources such as zooplankton and phytoplankton, are of particular interest. *Clupeiformes* represent a group of species characterized by high nutrient content, as they reside in the surface waters of oceans and open seas. These species have evolved to swim rapidly and continuously, enabling them to undertake long-distance migrations in pursuit of prolific plankton regions. *Anadromous* species migrate from freshwater to

Table 1
A comprehensive overview of the marine species and their lipid composition.

Fish

Species	Co-Product	PUFAs	Omega-3	n-6/3	EPA	DHA	References
Champsocephalus gunnari	Brain	0 %	0 %	-	0 %	0 %	(Lee et al., 2022)
	Liver	2.29 %	1.34 %	0	1.34 %	0 %	
	Stomach	35.6 %	32.7 %	0.02	15.9 %	14.9 %	
	Skin	27.8 %	25.9 %	0	15.6 %	8.0 %	
Clupea harengus	heads, viscera, tails, and fins	35.5 %	26.4 %	0.34	5.6 %	9.2 %	(Monteiro, Domingues, & Calado, 2024)
	heads, frames, skin, and viscera	21.9 %	-	-	6.4 %	9.4 %	
Dicentrarchus labrax	Heads	28.0 %	12.4 %	1.21	3.0 %	5.1 %	(Malcorps, Newton, Sprague, Glencross, & Little, 2021)
	Frames	29.4 %	13.1 %	1.19	3.2 %	5.2 %	
	Skin	33.8 %	16.6 %	1.00	4.0 %	7.5 %	
	Trimmings	27.3 %	11.0 %	1.43	2.6 %	4.3 %	
	Viscera	27.9 %	10.7 %	1.55	2.4 %	4.0 %	
Gadus morhua	skeletal frames, viscera, and heads.	32.1 %	-	-	8.9 %	13.3 %	(Monteiro et al., 2024)
	Liver	24.7 %	-	-	7.7 %	11.4 %	
Notothenia rossii	Brain	32.7 %	32.2 %	0.02	9.8 %	22.0 %	(Lee et al., 2022)
	Liver	26.0 %	21.8 %	0.13	8.4 %	11.5 %	
	Stomach	41.6 %	30.8 %	0.32	11.3 %	18.6 %	
	Skin	35.0 %	31.0 %	0.09	16.2 %	10.7 %	
Salmo salar	Heads	35.4 %	27.7 %	0.28	8.4 %	12.1 %	(Haq, Ahmed, Cho, & Chun, 2016; Malcorps et al., 2021)
	Heads	31.9 %	16.3 %	0.93	3.2 %	4.8 %	
	Frames	31.9 %	15.9 %	0.98	3.0 %	4.6 %	
	Skin	31.9 %	15.4 %	1.05	2.8 %	4.0 %	
	Trimmings	32.0 %	15.9 %	0.98	3.0 %	4.0 %	
	Viscera	25.0 %	10.4 %	1.37	1.6 %	2.3 %	
Scomber australasicus	Head	39.9 %	36.6 %	0.09	9.1 %	21.9 %	(Ahmmed et al., 2021; Ahmmed, Bunga et al., 2020; Ahmmed, Ahmmed, et al., 2020; Tanbirul Haque, Asaduzzaman, & Chun, 2014)
	Skin	38.1 %	34.8 %	0.09	9.6 %	19.5 %	
	Roe	47.0 %	44.4 %	0.06	11.3 %	27.5 %	
	Male gonads	44.7 %	42.5 %	0.05	12.1 %	24.7 %	
Scomber scombrus	Heads	25.4 %	-	-	3.6 %	9.3 %	(Oladapo Abiona et al., 2021; Tanbirul Haque et al., 2014)
	Gills	12.3 %	-	-	1.0 %	1.7 %	
Scophthalmus maximus	Frames	36.5 %	21.7 %	0.64	5.2 %	7.9 %	(Malcorps et al., 2021)
	Skin	37.4 %	22.6 %	0.62	5.2 %	8.9 %	
	Trimmings	37.5 %	22.8 %	0.61	4.9 %	9.8 %	
	Viscera	33.3 %	17.7 %	0.86	2.7 %	7.6 %	
	Heads	36.8 %	22.5 %	0.61	4.4 %	11.6 %	
Sparus aurata	Skin	29.9 %	13.2 %	1.21	2.3 %	5.5 %	
	Trimmings	29.6 %	13 %	1.23	2.2 %	5.4 %	
	Viscera	28.8 %	12.9 %	1.20	1.7 %	5.9 %	
	Frames	28.5 %	12.3 %	1.27	2.2 %	4.8 %	
	Heads	28.4 %	12.7 %	1.20	2.2 %	5.2 %	
	Gills	31.2 %	11.9 %	1.62	1.9 %	4.1 %	(Pateiro et al., 2020)
	Guts	33.1 %	12.1 %	1.75	1.8 %	3.5 %	
	Heads	33.8 %	14.0 %	1.41	2.8 %	5.0 %	
	Liver	32.2 %	13.6 %	1.38	1.9 %	4.9 %	
	Skin	33.2 %	12.9 %	1.57	2.0 %	4.0 %	
	Fishbone	33.8 %	13.6 %	1.48	2.8 %	4.6 %	
Thunnus thynnus	Minced side streams	33.2 %	29.9 %	0.06	9.9 %	13.6 %	(Ahmed, Haq, Cho, & Chun, 2017; Messina et al., 2022)
Seriola quinqueradiata (Yellowtail fish)	Viscera	30.2 %	0.95 %	7.6 %	6.9 %	30.2 %	(Franklin, Haq, Roy, Park, & Chun, 2020)

Algae

Genus	PUFAs	Omega-3	n-6/3	EPA	DHA	References
Chlorococcum sp.	23.2 %	13.8 %	0.9 %	8.9 %	3.4 %	(Conde et al., 2021; Shiels et al., 2021)
Chlamynodomonas reinhardtii	43.5 %	7.4 %	1.5 %	3.2 %	1.8 %	(Zou et al., 2023)
Schizochytrium sp., *Crypthecodinium cohnii*	27.8 %	31.6 %	0.8 %	0.5 %	33.1 %	(Abbas et al., 2023)
Coelastrella terrestris	21.7 %	7.2 %	1.3 %	2.3 %	0.5 %	(Doppler et al., 2022)
Ceramwm strtctum	43.6 %	18.2 %	1.6 %	3.9 %	2.4 %	(Ahmmed, Bunga et al., 2020; Ahmmed, Ahmmed, et al., 2020)
Cystosteira crinite	40.1 %	22.8 %	0.5 %	4.7 %	3.1 %	
Euglena gracilis	18.9 %	16.8 %	1.2 %	2.1 %	17.3 %	(Yao et al., 2022)
Heterosigma akashiwo	14.6 %	20.4 %	0.5 %	19.4 %	2.2 %	(Sun et al., 2020)
Nannochloropsis oceanica	57.1 %	31.2 %	0.7 %	29.4 %	< 1 %	(Jadhav and Annapure, 2023)
Phaeodactylum tricornutum	13.2 %	31.7 %	0.6 %	23.7 %	4.9 %	(Sun et al., 2023)
Ulva lactuca, Caulerpa racemosa (Green seaweeds)	19.8 %	-	2.30 %	3.5 %	2.8 %	(Pangestuti et al., 2021)
Bacillariophyte, Rhodophyte, Chlorophyte, etc.	22.9 %	29.1 %	1.7 %	8.4 %	3.3 %	(Linares-Maurizi et al., 2023)

Molluscs

Species	PUFA's	n-6/3	EPA	Omega-3	DHA	References

(continued on next page)

Table 1 (*continued*)

Fish							
Species	**Co-Product**	**PUFAs**	**Omega-3**	**n-6/3**	**EPA**	**DHA**	**References**
Crassostrea gigas (Pacific oyster)	23.7 %	0.90 %	6.8 %	-		5.5 %	(Lee, Haq, Saravana, Cho, & Chun, 2017)
Doryteuthis gahi	52.6 %	0.08	17.2 %	48.6 %		30.8 %	(Aubourg et al., 2021)
Illex argentinus	-	0.75	9.3 %	-		16.4 %	(Rodríguez et al., 2021)
Octopus vulgaris	49.3 %	0.34	12.9 %	36.8 %		22.2 %	(Méndez, Rodríguez, Aubourg, & Medina, 2023)
Pecten maximus	42.1 %	0.03	20.0 %	40.7 %		12.3 %	(Savoire et al., 2020)
Sepia officinalis	44.0 %	0.69	11.6 %	26.0 %		6.3 %	(Monteiro et al., 2024)

Crustaceans						
Species	**PUFAs**	**n-6/3**	**EPA**	**Omega-3**	**DHA**	**References**
Commercial crab(no specified species)	36 %	0.62	12 %	23 %	9.7 %	(Lv et al., 2022)
Commercial shrimp(no specified species)	40.9 %	2.2	6.3 %	12.3 %	4.1 %	
Lithodes santolla	40.0 %	0	20.5 %	40.0 %	14.4 %	(Cretton, Malanga, Sobczuk, & Mazzuca, 2021)
Pandalus borealis	41.1 %	0.11	21.1 %	37.1 %	13.9 %	(Phadtare, Vaidya, Hawboldt, & Cheema, 2021)
Penaeus vannamei	43.0 %	-	5.0 %	12.2 %	7.2 %	(Shen et al., 2021)
	37.4 %	2.53	2.2 %	10.6 %	6.2 %	
	38.1 %	1.35	3.3 %	16.2 %	10.4 %	
Pleoticus muelleri	52.0 %	0.03	21.5 %	50.3 %	22.3 %	(Cretton et al., 2021)

Krills						
Species	**PUFAs**	**Omega-3**	**n-6/3**	**EPA**	**DHA**	**References**
Frozen Antarctic krill	25.3 %	17.2 %	1.2 %	18.17 %	10.8 %	Wang et al., (2019))
	28.1 %	21.8 %	0.9 %	12.58 %	8.5 %	(Liu et al., 2019)
Freeze dried Antarctic krill	20.8 %	15.3 %	1.2 %	12.54 %	7.12 %	(Rose, Showman, Shen, Jaczynski, & Matak, 2024)
Euphausia superba	45.9 %	27.4 %	0.2 %	18.5 %	9.4 %	(Dalheim, Brage, Svenning, & Olsen, 2021; Lee, Haque, Kim, Lee, & Chun, 2014)
	42.4 %	29.3 %	0.7 %	11.4 %	5.1 %	

marine environments. *Salmoniformes* represent a significant source of EPA and DHA. The unique lifecycle in this instance contributes significantly to its elevated nutritional value.

3.2. Algae

Algae are photosynthetic organisms that can be categorized into red, green, and brown varieties based on their pigment composition. These serve as essential sources of n-3 LCPUFAs, as they have the capability to synthesize n-3 LCPUFAs de novo. The presence of n-3 PUFA in marine organisms within the food chain is contingent upon the algal feedstock. Algae can be categorized into two distinct types based on their size, microalgae and macroalgae.

3.2.1. Microalgae

The chemical composition of microalgal lipids is multifarious and largely determined by type of species and environment under growth conditions (Jónasdóttir, 2019). Polar lipids in the form of phospholipids and glycolipids are the major lipid classes and constitute 41–92 % of total lipid material, followed by nonpolar glycerolipids and account for approximately 5–51 % (Ahmmed, Ahmmed, Tian, Carne, & Bekhit, 2020). Sterols also form part of the lipid fraction in most species. Fatty acid profiles are high in long-chain types, particularly those with 16–18 carbon atoms. Main examples are palmitic (C16:0), stearic (C18:0), oleic (C18:1n-9), palmitoleic (C16:1n-7), LA, ALA, γ-linolenic (GLA), and stearidonic acid (SDA). Certain species have longer-chain fatty acids (C20–C22), such as nutritionally important compounds like EPA, DHA, and DPA (Mimouni, Couzinet-Mossion, Ulmann, & Wielgosz-Collin, 2018). PUFAs in microalgae can vary from 10 % to 70 % of the total fatty acids, with phylum-specific differences. Chlorophytes tend to be rich in C18-PUFAs, whereas Rhodophytes and Glaucophytes show higher content of longer chain PUFAs such as Arachidonic acid (ARA) and EPA (Khonji et al., 2023). Among the Chromista phylum, ARA and EPA are common in Xanthophyceae and Eustigmatophyceae classes. EPA and DHA are characteristic in Haptophytes, Dinophytes, and Cercozoa. Variation in the content of LA and GLA is encountered in various taxa, with significant amounts in *Chamaesiphon polonicus* and *Heterococcus endolithicus*. Dinophyta species like *Crypthecodinium cohnii* are unique for their high DHA concentration (~40 %), and *Pyrocystis lunula* possesses exceptional DPA content (~41 %) (Pateiro et al., 2022). Environmental factors, more so water temperature and salinity, heavily influence fatty acid production. Increased temperature and salinity levels usually minimize DHA and EPA production, though in others, like in *Phaeodactylum tricornutum*, there might not be a significant impact of salinity (Nielsen et al., 2019). They are also a source of several phytosterols, i.e., β-sitosterol, stigmasterol, campesterol, brassicasterol, and ergosterol (Randhir, Laird, Maker, Trengove, & Moheimani, 2020). The taxonomic structure of sterols is different: cryptophytes, diatoms, and haptophytes usually contain 24α sterols, whereas green algae and dinoflagellates tend to have 24β forms (Kateryna et al., 2021). Certain microalgae, e.g., Pavlova species, also synthesize uncommon sterols like pavlovols. These bioactive sterols have also shown health-benefiting properties such as antioxidant, cholesterol-lowering, anti-inflammatory, and even anticancer activity (Nielsen et al., 2019).

3.2.2. Macroalgae

Macroalgae or seaweeds are relatively simple autotrophic organisms that do not have much tissue differentiation. They are taxonomically classified into three broad groups: Chlorophyta (green algae), Rhodophyta (red algae), and Phaeophyceae (brown algae). Rhodophyta is the oldest group and is the largest group of the three, and Phaeophyceae are the brown algae that include *Laminaria spp*. and *Fucus spp*. belonging to the phylum Ochrophyta. Chlorophyta is the group that includes species like *Ulva lactuca.* Macroalgae possess unique lipid composition profiles that are different from those of microalgae. Despite their moderate amount of lipid content 0.79–7.87 % dry weight, they remain a PUFAs-rich source like LA, ALA, SDA, EPA, and DHA. These fatty acids can contribute 10–70 % of the total fatty acid composition (Santos, Guihéneuf, Fleming, Chow, & Stengel, 2019). Most macroalgae possess a desirable n-6 to n-3 PUFA ratio (0.1–3.6), which is nutritionally ideal. Different groups contain different levels of fatty acids. Green algae contain a higher concentration of C18 PUFAs such as LA and ALA. Red algae contain more C20 fatty acids such as EPA and ARA, and brown algae contain a balanced concentration (Farobie et al., 2019).

Macroalgae are generally poor in DHA, and some of them are even DHA-free. Exceptions exist: *Sargassum natans*, for example, contains high DHA (970 µg/g of total FAs), together with ARA and EPA. The same was indicated by (Schmid, Guihéneuf, & Stengel, 2014), who listed ALA and SDA as the predominant omega-3s in different macroalgal species along the Irish coast. Macroalgae display a wide variety of phospholipids, with concentrations between 3.5 % and 20 %, alongside neutral lipids that can fluctuate greatly from 1 % to 97 %. These levels are influenced by the specific species and the conditions under which they are cultured (Peñalver et al., 2020). Phosphatidylglycerol (PG) is a predominant phospholipid in green algae, accounting for 15–45 % of the total phospholipids, while phosphatidylcholine (PC) constitutes 60 % of the total phospholipids in red algae. Brown algae comprise both PC and PE, accounting for 11.5–29.6 % of the total phospholipids. Phosphatidylcholine was the most common phospholipid in most of the species that were studied, but the concentrations of it varied a lot from species to species, ranging from 1.8 % to 52.7 % (Galindo et al., 2022). The second most prevalent PL was PE, which represented between 17.9 % and 46.2 % of the total PLs. Macroalgae are rich in carotenoids, phytosterols, antioxidants, and vitamins, all of them can enhance the health benefits of algal oil and improve its storage stability (Ahmmed, Bunga et al., 2020; Ahmmed, Ahmmed, et al., 2020). The content of DHA is often minimal or occasionally non-existent in the majority of macroalgae species.

3.3. Shellfish

Shellfish are aquatic organisms that contain a variety of bioactive substances. Molluscs and crustaceans classified as shellfish have lipid levels between 0.5 % and 2.5 %, mostly in the form of phospholipids and sterols. Fatty acids, comprising about 75 % of total lipid in molluscs and 65 % in crustaceans, are the primary constituents of phospholipids (Gulzar, Raju, Nagarajarao, & Benjakul, 2020). It is important to remember that just 50 % of the capture may consist of the edible portions of these aquatic animals, which include muscle, belly flap, and subcutaneous tissue. Nevertheless, they are remarkable source of omega-3 fatty acids. Omega-3 long-chain PUFAs, particularly DHA, C22:6 and EPA, C20:5, are abundant in shellfish lipids (Pateiro et al., 2022). In general, PUFA content is greater than that of monounsaturated fatty acids (MUFAs) and saturated fatty acids (SFAs). Although they are lower than in oily fishlike mackerel and salmon, the contents of EPA and DHA in shellfish normally range from 300 to 500 mg% (raw muscle). n-3 PUFA (16.6 %–57.1 %) is greater in Mediterranean cephalopods and crustaceans than n-6 PUFA (4.1 %–10.6 %), with an n-3/n-6 ratio > 1 (Aubourg, Trigo, Prego, Cobelo-García, & Medina, 2021). The range of total PUFA content is 21.7 %–61.5 %, which is higher than that of SFA (16.9 %–41.3 %) and MUFA (9.1 %–42.8 %). The EPA and DHA levels of Mediterranean red shrimp are high. Additionally, Korean shellfish have low MUFA and high EPA and DHA. Norway lobster and prawn species include 26 %–35 % MUFA, 23 %–27 % SFA, and 42 %–48 % PUFA. 33 % SFA, 22 % MUFA, and 29 % n-3 PUFA are reported in brown shrimp fat (1 % w/w); 41 % and 32 % of PUFA are made up of EPA and DHA, respectively. With DHA/EPA ratios between 1.05 and 2.15, white and black tiger shrimp exhibit 42 %–44 % n-3 PUFA. Lipid content in both wild and farmed shrimp is around 1 %, with C16:0, C18:0, C20:5n-3, and C22:6n-3 being important fatty acids (AlFaris et al., 2022). Cephalopods are high in EPA and DHA and have around 2 % crude fat. They include 43.6 %–56.5 % PUFA, 28.2 %–35.3 % SFA, and 4.4 %–9.5 % MUFA, respectively. DHA is in charge. Moreover, clams, snails, and mussels have significant PUFA contents (Venugopal & Gopakumar, 2017). Total lipid was found in an amount of 2.54 $\pm$ 0.32 % of wet weight of the oysters. There were six types of total lipid found in the oysters, including hydrocarbons and wax (HW), triacylglycerol (TAG), free fatty acids (FFAs), sterol (ST), polar lipid, and monoalkyldiacylglycerol (MADAG).

3.3.1. Crustaceans

The lipid composition in crustaceans varies based on the specific part being analyzed. Triglycerides make up most of the lipids in the hepatopancreas. There are also minimum amounts of cholesterol, phospholipids, diglycerides, cholesterol esters, and free fatty acids (Pateiro et al., 2022). In muscle and nerve, the primary components are phospholipids and cholesterol, and certain amounts of triglycerides, diglycerides, and free fatty acids may also be present. This group encompasses lobsters, shrimp, krill, barnacles, crabs, and prawns. Furthermore, factors such as geographical location, season, nutrition, and species influence the contents, composition, and fatty acid profile (Xie et al., 2019). Crab, lobster and shrimp, which exemplify the crustacean group, have low-fat contents in their edible parts, ranging from 0.5 % to 1.5 %. Krill serves as an important source of n-3 LCPUFA, likely because the fatty acids are integral to their diet. Pacific krill exhibit PUFA contents varying from 35 % to 50 %, comprising 15 %–20 % of EPA and 8.2 %–20.6 % of DHA. In contrast, Atlantic krill demonstrate elevated levels of EPA at 28.2 % and DHA at 18 %. Antarctic krill (*Euphausia superba*) is seen as a viable alternative source of marine lipids, garnering significant interest from both academics and industries. Antarctic krill, akin to fish lipids, is recognized for its higher concentrations of n-3 PUFA, (30–45 %), mostly including DHA (6–13 %) and EPA (11–20 %) (Luo et al., 2024). Significant levels of these fatty acids were also observed in shrimps, with concentrations reaching 15 %, 17 %, and 1.35 % for EPA, DHA, and DPA, respectively. The fatty acid profile of *Panulirus homarus* shows that EPA (24.32 %–25.17 %) and C16 (19.18 %–22.14 %) are the main fatty acids. DHA (4.62 %–6.32 %) is also present in significant amounts. Furthermore, there exist additional species that, while currently lacking commercial value, exhibit a lipid profile indicative of their potential, as they offer high-value constituents. This pertains to a species of squat lobster classified under the genus *Munida spp.* The lipid content varied between 0.80 % and 0.96 %, comprising sterols (12.15 %–13.54 %), triacylglycerols (0.06 %–1.20 %), phospholipids (65 %–68 % of total lipids) and free fatty acids (1.15 %–2.25 %). In terms of fatty acids, the most prevalent group was PUFA, comprising 50.4 %–55.3 %, with notable levels of EPA at 16.87 %–19.95 % and DHA at 28.79 %–29.38 %. Significant findings were also identified for certain saturated fatty acids (C16:0, 16.0 %–18.2 %) and monounsaturated fatty acids (C18:1n-9, 16.06 %–17.11 %) (García-Soto, Trigo, Barros-Velázquez, & Aubourg, 2017). In contrast to fish, crustaceans exhibited elevated sterol levels, with concentrations ranging from 120 to 160 mg per 100 g in octopus, prawns, scallops, and squid. Cholesterol remains the primary sterol detected, with concentrations exceeding 27 mg/100 g. Conversely, reduced values were observed for stigmasterol (3.5 mg/100 g) (Pateiro et al., 2022).

3.3.2. Krills

The primary crustacean source of PL n-3 is the small oceanic krill, a shrimp-like zooplankton that consumes n-3 LCPUFA-enriched microalgae and gather n-3, comprising nearly 18 % EPA and 9.5 % DHA of total fatty acids in their body. Krill oil is regarded as a very effective source for n-3 than fish oil. Researchers observed that the elevated phospholipid content of krill oil leads to a superior absorption rate in plasma and the brain (Ahn et al., 2018). Several clinical and subclinical trials involving rats and humans have validated the health benefits of krill oil (Lavado García et al., 2018). The lipid content in krill ranges from 2 % to 6 %, varying with their sexual maturity. Phospholipids, triacylglycerols, and free sterols make up most of the lipids in krill oil. They make up about 39–40 % of the total lipid content, followed by 25–30 % triacylglycerols, 15–20 % free sterols, and 1.5–2.3 % wax esters (Tomé-Carneiro et al., 2018). The lipid composition of Pacific krill includes TAG ranging from 3.4 % to 27.3 %, PE from 3.4 % to 17.5 %, and PC between 36.2 % and 53.8 %. Additionally, sterols are present at levels of 5.4–12.9 %, while FFA varies from 6.9 % to 22.2 %. Notably, PUFA constitutes 35–47 % of the total fatty acids, with EPA making up 15–25 % and DHA ranging from 8.4 % to 20.4 % (Wang, Xue, Zhang, &

Wang, 2018). It is noteworthy that the PL portion has a higher concentration of n-3, specifically EPA and DHA, in comparison to TAG. Small amounts of TAG are found in Atlantic krill, between 1 % and 3 %. Phospholipids make up 20–33 % of their lipid content, while polar non-phospholipids make up 64–77 %. Notably, the phospholipid fraction has a lot more n-3 long-chain PUFAs than TAG fraction. It has 45.9 % total n-3, 27.6 % EPA, and 19 % DHA, while the TAG fraction only has 5–6 % total omega-3, 1.5 % DHA, and 2.5 % EPA. Like algae, krill also has a low concentration of DPA. For example, *Euphausia pacifica* comprises 0.3–0.6 % DPA of the total fatty acid. Nonetheless, variations in lipid composition and fatty acid profiles can occur based on season, geographical location, species, and extraction technology (Xie et al., 2019). The potential of krill as a source of n-3 PLs is noteworthy; however, the commercial harvesting of krill remains a contentious issue due to its significance as a primary source of n-3 in the oceanic food web. The ongoing extraction on krill for the marketable production of krill oil supplements is disrupting the natural equilibrium of food resources within the marine ecology, potentially endangering other species, including whales that rely on krill as a food source (Ahmmed, Bunga et al., 2020; Ahmmed, Ahmmed, et al., 2020).

4. Biochemical characterization of marine lipids

4.1. Composition and structure

Marine lipids include a structurally and functionally diverse array of biomolecules much more varied than fatty acids, including the complex lipid categories phospholipids, glycolipids, betaine lipids, sterols, and sulfolipids. They are categorized into broad lipid classes such as glycerolipids, glycerophospholipids, sphingolipids, and prenol lipids according to the LIPID MAPS classification (Table 2). Among these, omega-3 fatty acids, particularly EPA and DHA, hold considerable significance due to their associated health benefits. Besides these general fatty acids, marine lipids also contain distinctive classes like sulfonolipids and other bioactive compounds, which have been demonstrated to serve crucial roles in cell signaling, membrane dynamics, and inflammation regulation (Roman et al., 2024). The particular makeup and distribution of these classes of lipids can be very different based on the marine organism, trophic level, and environmental conditions like diet, temperature, and habitat (Abraúl et al., 2023). For instance, lipid compositions of marine fungi and microalgae respond strongly to varying growth conditions such as nutrient levels and light intensity, with the latter changing SFAs, MUFAs, and PUFAs ratios. Likewise, the distribution pattern of complex lipids like phospholipids and glycolipids plays a pivotal role in preserving membrane fluidity, integrity, and cellular function within marine organisms (Lakatos et al., 2023).

In terms of structure, marine lipids typically have long-chain fatty acids and unique functional groups, which account for their high bioactivity and likely health-promoting effects when ingested as components (Jaworowska & Murtaza, 2022). Recent improvements in lipidomics technology have facilitated broader profiling of marine lipidomes, shedding new light on their metabolic pathways, ecological functions, and uses in functional foods and nutraceuticals A thorough information of marine lipid composition is necessary to investigate their potential health advantages and applications in functional foods and nutraceuticals (Abraúl et al., 2023).

4.2. Extraction and purification methods

The extraction and purification of marine lipids are crucial steps for their characterization and application. Breaking up the cells prior to lipid extraction is crucial for enhancing the mass transfer on the solvent extraction (Patel, Mikes, & Matsakas, 2018). A range of physical, chemical, biological (enzymatic) and mechanical pretreatments is utilized to decompose the tough cell wall of oleaginous biomass (Patel et al., 2018). The intricate and inflexible cell wall of microalgae obstructs solvent penetration, leading to a diminished extraction of lipids. As a result, extracting lipids from microalgae requires the disruption of the cell wall through appropriate pretreatments, followed by lipid extraction using solvents. Furthermore, the application of pretreatments allows for an adequate amount of lipids to be achieved from the wet biomass, effectively removing the need for the expensive dehydration process. Conventional techniques like solvent extraction have been extensively employed; yet, they frequently result in the co-extraction of undesired compounds, complicating the analysis (Gerhardtova et al., 2024). Recent innovations have led to the development of more efficient extraction techniques, including supercritical fluid extraction and enzymatic methods, which provide higher purity and yield of marine lipids. The utilization of supercritical CO_2 has shown significant efficacy in extracting omega-3 fatty acids from fish oils, simultaneously minimizing the degradation of sensitive compounds (Gerhardtova et al., 2024).

The potential of marine fungus as sources of bioactive chemicals has led to lots of interest in the extraction of lipids from these organisms. Researchers discovered that the fatty acid profiles of marine fungus might vary significantly based on the cultures' age, suggesting that improving culture conditions could increase the amount and quality of lipids produced (Table 3) (Abraúl et al., 2023). Additionally, scientists have studied hydrothermal extraction methods for marine macroalgae, which allow for the efficient recovery of lipids while preserving their bioactive properties. Sustainable utilization of marine resources depends on the development in extraction methods, which helps to recover vital lipids and reduces environmental effect (Gerhardtova et al., 2024).

4.3. Analytical techniques

A variety of methods can be employed to analyze the lipid fractions after solid-phase extraction or thin-layer chromatography, including Direct Injection (DI)-MS, Nuclear Magnetic Resonance (NMR) spectroscopy, Gas Chromatography with Flame Ionization Detector (GC-FID) or GC-MS, High-Performance Liquid Chromatography (HPLC)-MS, and Non-Aqueous Capillary Electrophoresis (NACE) (Alves, Domingues, & Domingues, 2018), additionally, solvent extraction techniques such as acid-base extraction, liquid-liquid extraction, solid-liquid extraction, single-solvent extraction, and supercritical fluid extraction are used (Alves et al., 2018).

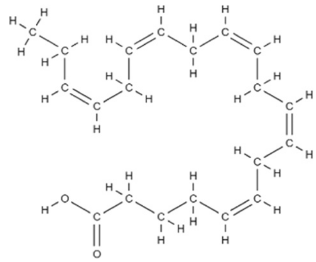
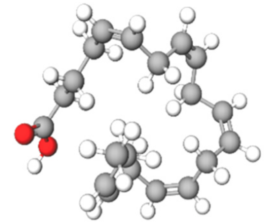
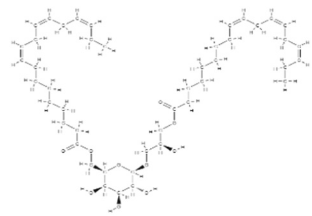
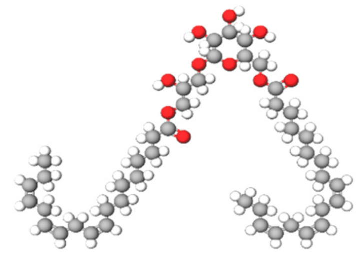
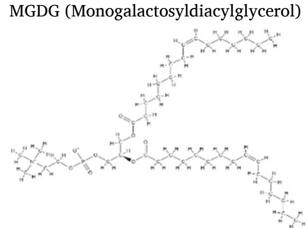
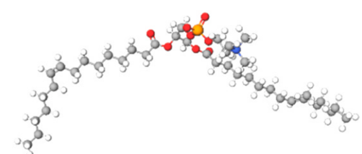
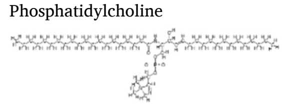
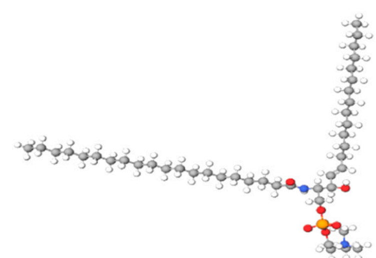
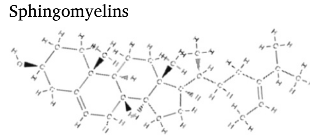
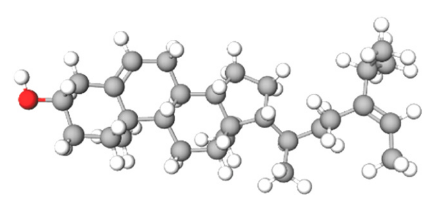
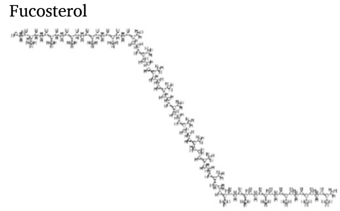
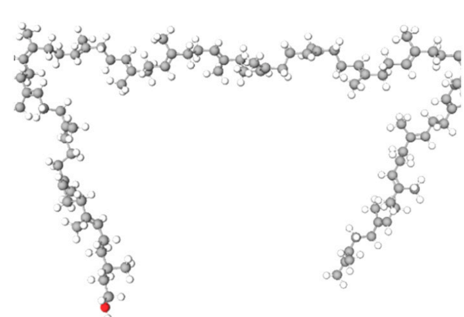
4.3.1. Profiling of fatty acids employing GC-based techniques

Fatty acids in marine oils are often measured using gas chromatography (GC), especially when combined with mass spectrometry (GC-MS) or flame ionization detection (GC-FID). Fatty acids must be transesterified into more volatile derivatives, usually fatty acid methyl esters (FAMEs), before GC analysis can be performed (Ryckebosch et al., 2014). Particularly for samples strong in long-chain, highly unsaturated fatty acids, such as DHA and EPA, which are common in marine sources, this derivatization phase is crucial (Costa, Domingues, & Alves, 2023). While GC-MS enables improved chemical identification via retention time and mass spectrum pattern analysis, GC-FID delivers dependable quantitative data. Because of this, GC-MS is especially well suited for marine matrices that include uncommon or co-eluting fatty acids, as those present in deep-sea species or microalgae (Breuer et al., 2013).

4.3.2. Characterization of sterols

Many types of sterols are often found in marine lipid extracts. These may exist in their free form or conjugated as glycosides and esters. Conjugated forms of sterols need hydrolysis in order to liberate the sterol moieties, while free sterols may be examined immediately using GC techniques (Randhir et al., 2020). Phytosterols like fucosterol and stigmasterol, as well as cholesterol, are often discovered in marine samples like fish oils and macroalgal extracts. In more recent times, intact sterol conjugates have been analyzed using liquid chromatogr'aphy coupled with mass spectrometry (LC-MS). This method offers great sensitivity

Table 2
Lipid diversity: the eight major classes of lipids with 2D and 3D representation.

Lipid Class	Example and Source	2D	3D
Fatty acids	EPA, DHA from fish & microalgae	 EPA	
Glycerolipids	TAGs in fish oil, MGDG in algae	 MGDG (Monogalactosyldiacylglycerol)	
Glycerophospholipids	Phosphatidylcholine in Krill oil	 Phosphatidylcholine	
Sphingolipids	Sphingomyelins in Sea cucumber, coral	 Sphingomyelins	
Sterols	Cholesterol (fish), fucosterol (algae)	 Fucosterol	
Prenols	Dolichols in sponges		

(continued on next page)

Table 2 (*continued*)

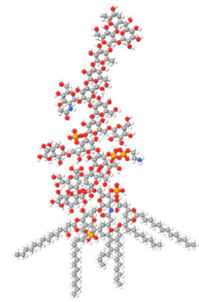
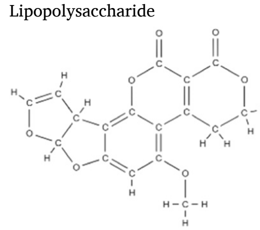
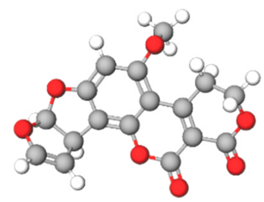
Lipid Class	Example and Source	2D	3D
		Dolichols	
Saccharolipids	Lipopolysaccharide in marine bacteria		
		Lipopolysaccharide	
Polyketides	Marine sponges & fungi		
		Polyketides	

Table 3
Phospholipids from various marine sources and their extraction conditions.

Sample	Type of process/ solvent	Temperature	Extraction time	Bioactive compounds extracted	References
Atlantic Salmon	Ethanol	45 °C	2.5hrs	Astaxanthin and ω-3 fatty acids	(Ali-Nehari & Chun, 2012; Haq & Chun, 2018)
Rainbow trout muscle	Hexane	40 °C	12hrs	PhospholipidsLecithin	(Topuz et al., 2021)
Hoki roe	Ethanol: Hexane (2:1)	Cool environment	10 min (10,000 rpm)	Phospholipids: 4 %Lecithin: 5.21 %	(Ahmmed, Bunga et al., 2020; Ahmmed, Ahmmed, et al., 2020)
Engraulis japonica	Ethanol	Optimum temperature	24hrs	PC:70 %, PE:30 %PA: 3.0 %, PI: 2.0 %	(Haq, Suraiya, Ahmed, & Chun, 2021)
Scomber japonicus	Ethanol (HPLC grade)	Optimum temperature	12hrs	PhospholipidsPC: 20, PE: 65,Others: 12.45–0.05	(Haq et al., 2021)
Euphausia superba	Ethanol	Optimum temperature	12hrs	PhospholipidsPC: 80 %, PE: 15 %, PI: 0.9 %	(Haq et al., 2021)
	Ethanol, Hexane and Acetone	45 °C	2.5hrs	Neutral lipids	(Ali-Nehari & Chun, 2012)
Cololabis saira	Acetone	Optimum temperature	5hrs	Phospholipids	(Zhang et al., 2018)
Todarodes pacificus	Ethanol	Optimum temperature	12hrs	Phospholipids (3.90 %)PC: 80 %, PE: 13.5 %, Others 6.5 %	(Haq et al., 2021)
Sardina pilchardus	Protamex	40–50 °C	30hrs	Phospholipids	(Haq et al., 2021)

and molecular specificity without requiring chemical hydrolysis (André et al., 2021).

4.3.3. Lipid class separation and analysis

Neutral and polar fractions are often separated from marine lipids. For this, methods like solid-phase extraction (SPE) and thin-layer chromatography (TLC) are used. Triacylglycerols (TAGs), phospholipids, and glycolipids are among the lipid classes that are often resolved and quantified using high-performance liquid chromatography (HPLC) once they have been separated (Morales, Aflalo, & Bernard, 2021). Detection can be achieved using ultraviolet (UV) absorbance or, more effectively, by coupling HPLC with mass spectrometry. For best resolution, polar lipids found in seaweed and microalgae, such as monogalactosyldiacylglycerols (MGDGs) and sulfoquinovosyldiacylglycerols (SQDGs), often call for specific HPLC techniques (Riccio, De Luca, & Lauritano, 2020).

4.3.4. Recent advances in extraction and characterization of marine lipids

Recent years have seen significant progress in the extraction and analytical characterization of marine lipids (Table 4). Novel eco-friendly approaches such as supercritical CO_2 extraction, enzyme-assisted extraction, and microwave-assisted techniques have replaced conventional solvent methods, offering higher purity, improved yield, and minimal oxidative degradation. These advances ensure better preservation of sensitive omega-3 fatty acids and phospholipids while reducing environmental impact. Simultaneously, high-resolution lipidomics employing LC-MS and GC-MS technologies has enabled detailed profiling of complex lipid classes, providing deeper insight into their structure, function, and nutritional value. Together, these developments mark a shift toward sustainable, precise, and data-driven strategies for exploring marine lipid diversity and functionality.

4.3.4.1. Supercritical CO_2 extraction. Supercritical CO_2 ($SC\text{-}CO_2$)

Table 4
Comparison of major extraction methods for marine lipids.

Extraction Method	Key Operating Conditions	Typical Yield / Efficiency	Advantages	Limitations	Sustainability Aspects	Reference
Supercritical CO_2 Extraction	Pressure: 250–350 bar; Temp: 40–60°C; Co-solvent: Ethanol (0–10 %)	High (85–95 %)	Non-toxic, solvent-free, selective for PUFAs, minimal oxidation	High equipment cost, limited for polar lipids	Environmentally safe, recyclable CO_2, green process	(Haq & Chun, 2018)
Enzymatic Extraction	Temp: 35–55°C; pH: 6.5–8.0; Enzymes: Proteases/Lipases	Moderate–High (70–90 %)	Mild, preserves bioactivity, minimal solvent use	Slower reaction rate, enzyme cost	Biodegradable reagents, low energy demand	(Patchimpet et al., 2021)
Microwave-Assisted Extraction (MAE)	Temp: 80–100°C; Time: 10–20 min; Solvent: Ethanol/Water	Moderate–High (75–90 %)	Fast, energy efficient, good for algae and seaweed	Risk of overheating, limited scalability	Green solvents, reduced time and energy use	(Quitério et al., 2022)
Ultrasound-Assisted Extraction (UAE)	Frequency: 20–40 kHz; Time: 10–30 min; Solvent: Ethanol/Hexane	Moderate (65–80 %)	Enhanced cell disruption, shorter time	Possible lipid oxidation if overheated	Reduced solvent use, low cost	(Mishra et al., 2025)
Solvent Extraction (Bligh & Dyer / Folch)	Solvent: Chloroform-Methanol; Temp: Room–50°C	High (80–95 %)	Widely validated, high recovery	Toxic solvents, environmental hazard	Poor sustainability, disposal concerns	(Bouizgma et al., 2025)

extraction has emerged as one of the most efficient and eco-friendly methods for isolating marine lipids (Haq & Chun, 2018). By operating above CO_2's critical temperature (31.1°C) and pressure (73.8 bar), the technique allows selective solubilization of non-polar compounds such as triglycerides and sterol esters while preserving thermolabile omega-3 polyunsaturated fatty acids (PUFAs). The tunable density of the supercritical fluid enables fine control over extraction selectivity and yield. Co-solvents such as ethanol or methanol are often introduced to enhance recovery of polar lipids, including phospholipids and glycolipids. Recent studies report that SC-CO_2 extraction yields up to 95 % recovery efficiency with minimal oxidation, positioning it as a sustainable alternative to traditional solvent-based techniques (Herzyk, Piłakowska-Pietras, & Korzeniowska, 2024).

4.3.4.2. Enzymatic extraction. Enzyme-assisted extraction represents a mild, green approach that minimizes chemical residues and thermal degradation. Hydrolytic enzymes, particularly proteases and lipases facilitate cell wall disruption, releasing intracellular lipids from complex marine matrices such as algae, krill, and shellfish (Shivakumar, Serlini, Esteves, Miros, & Halim, 2024). Process parameters such as enzyme concentration, pH, and hydrolysis duration can be optimized to improve both yield and purity. The resulting lipid fractions exhibit higher bioactive integrity, especially in phospholipid-rich extracts. Enzymatic processes are increasingly combined with aqueous biphasic systems and ultrasound pretreatments to enhance efficiency while maintaining environmental compatibility (Patchimpet, Sangkharak, Eiad-ua, & Klomklao, 2021).

4.3.4.3. Microwave-assisted extraction. Microwave-assisted extraction (MAE) utilizes electromagnetic radiation to heat intracellular moisture, causing rapid cell rupture and improved solvent penetration. Compared with Soxhlet or Bligh and Dyer methods, MAE significantly reduces extraction time and solvent consumption. It is particularly advantageous for microalgal and seaweed biomass, where dense cell walls hinder lipid release (Quitério, Grosso, Ferraz, Delerue-Matos, & Soares, 2022). Studies demonstrate that optimized MAE conditions (80–100°C, 10–20 min) can achieve lipid yields comparable to SC-CO_2 methods with reduced oxidative degradation. Coupling MAE with green solvents such as ethanol further enhances sustainability and scalability (Bouizgma, Rabbah, Abbas, & Abourriche, 2025).

4.3.4.4. Advanced lipidomic approaches. Liquid chromatography-electrospray ionization tandem mass spectrometry (LC-ESI-MS/MS) is widely used in modern marine lipidomics research. From complete lipid extracts or separated fractions, this method allows for the simultaneous identification and structural characterization of many lipid species. For the analysis of complex marine lipidomes, high-resolution mass spectrometry (HRMS) and its tandem variant (HRMS/MS) are very useful (Paroni et al., 2019; Schmid et al., 2014). These techniques provide comprehensive details on molecule structure, including fatty acyl chain makeup and double bond placement (Gao, Liu, Jin, & Wang, 2019). Additionally, they aid in the identification of species-specific markers or oxidized lipids, which supports taxonomic and nutritional analyses (Rey et al., 2022).

5. Sustainability challenges and circular bioeconomy in marine lipid production

The rapid expansion of marine lipid production has raised growing concerns regarding sustainability, ecological balance, and long-term resource availability (Albrektsen et al., 2022). Although marine lipids are globally recognized for their nutritional and therapeutic importance, large-scale harvesting of fish and other marine organisms can exert significant pressure on aquatic ecosystems (Albrektsen et al., 2022). Overexploitation of pelagic fish for oil extraction, by-catch issues, and inefficient processing of by-products contribute to biodiversity loss and resource depletion (Pincinato, Bevilacqua, de Araújo, & del Favero, 2025). Addressing these challenges is crucial for aligning marine lipid utilization with global sustainability goals and responsible ocean stewardship.

A shift toward resource recovery and circular bioeconomy principles is emerging as a central strategy to ensure environmental sustainability. Utilization of processing by-productssuch as fish heads, viscera, krill shells, and algal residues offers an effective approach to minimize waste and enhance value generation. These by-streams contain significant quantities of PUFAs, phospholipids, and antioxidants that can be recovered through eco-friendly extraction technologies (Pincinato et al., 2025).

Microalgae and other non-conventional sources represent another sustainable frontier in marine lipid production. Unlike capture fisheries, algal cultivation can be carried out in closed or semi-closed systems with controlled nutrient inputs and minimal land or freshwater requirements (Kurniawan et al., 2025). When coupled with renewable energy use and nutrient recycling, such systems contribute to carbon sequestration and climate resilience while producing high-quality omega-3 lipids (Kunj, Sahu, Singh, & Arya, 2025).

6. Health benefits of marine lipids

6.1. Anti inflammatory

Marine lipids from diverse sources demonstrate significant anti-inflammatory properties through various mechanisms. While microalgae represent important sources, the anti-inflammatory potential extends across multiple marine organisms. Microalgae-derived anti-inflammatory compounds have shown promising results in various studies. Glycolipids and neutral phospholipids separated from the total lipids of the Irish coast-isolated microalga *Chlorococcum sp.* demonstrated strong anti-thrombin and anti-Platelet-Activating Factor (PAF) activity in human platelets. Following further analysis of these fractions, cerebrosides, SQDG, and PC and PE molecular species were identified (Choudhury et al., 2020). Galactolipids with PUFA acyl chains (EPA) exhibit enhanced Nitric Oxide (NO) inhibitory activity relative to other acyl chains, thus attenuating inflammatory signalling. Recent evidence also emphasizes the importance of marine-derived phospholipids as key contributors to human health beyond their structural roles. These phospholipids exhibit significant bio-functional properties, including improved lipid absorption, membrane stabilization, anti-inflammatory potential, and neuroprotective effects. Marine phospholipids particularly those enriched with EPA and DHA, demonstrate superior bioavailability compared to neutral lipids, enhancing their physiological impact on cardiovascular, cognitive, and metabolic health (Haq & Suraiya, 2021)

Marine algae beyond microalgae also contribute significantly to anti-inflammatory activities. Researchers conducted experiments on BALB/c mice to evaluate the anti-inflammatory effects of ARA, SDA, and EPA fatty acids sourced from the brown seaweed *Undaria pinnatifida*. The results revealed that both SDA and EPA effectively reduced inflammation caused by Phorbol 12-myristate 13-acetate (PMA) in the ears of the mice, as evidenced by a reduction in edema, erythema, and blood flow (Monteiro et al., 2024).

Fish and fish by-products represent another crucial source of anti-inflammatory marine lipids. Marine lipids, especially omega-3 polyunsaturated fatty acids like EPA and DHA, have shown remarkable neuroprotective activity by promoting cognition development, improving neuroplasticity, and alleviating the risk and advancement of neurodegenerative disorders like Alzheimer's and Parkinson's through anti-inflammatory, antioxidant, and membrane-stabilizing activities (Bălașa, Chircov, & Grumezescu, 2020; Naik et al., 2024). EPA and DHA compete with arachidonic acid for COX and LOX, shifting eicosanoid production toward less pro inflammatory mediators and specialised pro resolving mediators such as resolvins, protectins, and maresins (Fig. 3). They dampen NF kB and MAPK signalling, reduce IL 6, TNF alpha, and IL 1 beta, stabilise lipid rafts in immune cell membranes, and activate GPR120 to curb macrophage driven inflammation(Pateiro et al., 2021), providing anti-inflammatory benefits through their high PUFA content and favourable n-3/n-6 ratios (Fig. 3).

6.2. Cardioprotective

Marine lipids from various sources provide specific cardiovascular benefits through distinct mechanisms, with extensive clinical evidence supporting their cardioprotective effects. Krill oil demonstrates superior cardiovascular benefits due to its unique phospholipid structure. They are found to improve endothelial function through enhanced nitric oxide bioavailability and reduced oxidative stress, lower triglycerides via down regulation of SREBP 1c and reduced VLDL secretion, and lessen platelet aggregation by decreasing thromboxane A2 and PAF activity (Sherratt, Libby, Dawoud, Bhatt, & Mason, 2024). They favour plaque stability, modestly reduce blood pressure, and show antiarrhythmic effects through modulation of cardiac ion channels and improved heart rate variability. Researchers observed that the elevated phospholipid content of krill oil leads to a superior absorption rate in plasma and the brain (Ahn et al., 2018). Several clinical and subclinical trials involving rats and humans have validated the health benefits of krill oil (Lavado García et al., 2018). The phospholipid-bound omega-3s in krill oil provide enhanced bioavailability compared to triglyceride-bound omega-3s in fish oil.

Fish-derived lipids show specific cardioprotective mechanisms. Clinical evidence demonstrates that omega-3 fatty acids from fish sources significantly reduce cardiovascular mortality and morbidity. The mechanisms involve modifying potassium, sodium, and calcium channels, showcasing antiarrhythmic effects, which result in decreased thromboxane synthesis and beneficial impacts on heart rate variability. These PUFAs modify ion channels to reduce the impulsivity of heart cells and inhibit atrioventricular conduction, significantly decreasing the likelihood of experiencing a prolonged QT interval (Kapoor, Kapoor, Gautam, Singh, & Bhardwaj, 2021). Salmon phospholipids demonstrate specific antithrombotic properties. Table 5 provides extensive evidence showing that salmon PL retains ability to inhibit platelet aggregation induced by PAF, thrombin, ADP, and collagen, demonstrating significant cardioprotective potential (Redfern et al., 2021; Tsoupras, Lordan,

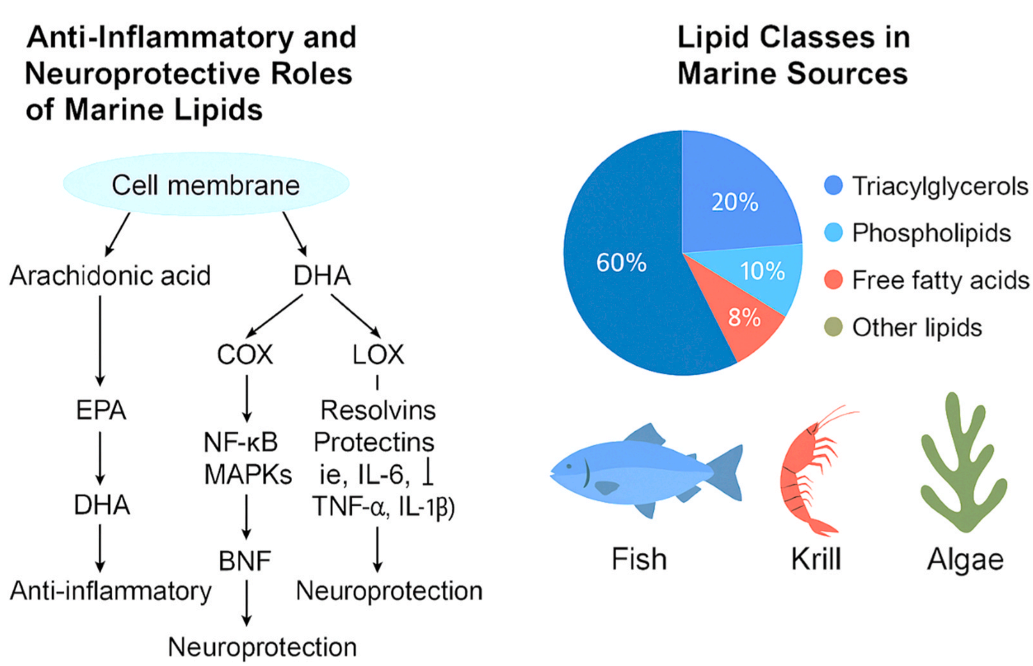


Fig. 3. Mechanistic pathways of anti-inflammatory and neuroprotective effects of marine lipids and comparative lipid class distribution across marine sources.

Table 5
Evidence on the health effects of marine lipid components from experimental, clinical, and epidemiological studies.

Study Design	Bioactive Lipid (Daily Dosage/ Amount in In Vivo Trials)	Reported effects	Models	Principal Impacts on Health	Further observations	Reference
In vitro study						
	Salmon PL	Anti-inflammatory and anti-thrombotic cardio-protective properties	Human platelets	Inhibited platelet aggregation induced by PAF and thrombin, similar to conventional salmon PL	Potential for novel supplements with cardio-protective properties	(Tsoupras, O'Keeffe, Lordan, Redfern, & Zabetakis, 2019)
	Polar lipids from Thermally treated salmon PL vs. raw salmon	Anti-inflammatory and anti-thrombotic properties	Human platelets	Salmon PL retains ability to inhibit platelet aggregation after heat treatment	Effective against PAF, thrombin, ADP, and collagen	(Redfern et al., 2021)
	By-products from fish	Anti-inflammatory and anti-thrombotic properties	Human platelets	Inhibited platelet aggregation induced by PAF, thrombin, ADP, and collagen	Potential supplements with cardio-protective properties	(Tsoupras et al., 2019)
	Meta-analysis					
	Intake of non- and dietary n-3 PUFA	CHD Effect	There were 7951 intervention individuals and 7855 control persons (1966–1999).	Decrease in the total death rate	Decrease in MI and unexpected death	(Tsoupras et al., 2022)
	EPA+DHA	Blood pressure	7 RCTs (2012–2014)	Decreased systolic blood pressure	> 2 g lowers blood pressure at the diastolic level	(Tsoupras et al., 2022)
Randomized Analysis						
	Vitamin D3 (2000 IU/24hrs) and fish n-3 PUFA (1 g/day)	Primary prevention of cardiovascular disease and cancer	25,871 participants in the United States were males aged 50 or older and women aged 55 or older.	n-3 PUFA supplementation did not reduce major cardiovascular events or cancer incidence compared to placebo.		(Manson et al., 2019)
	Fatty fish added to a Mediterranean diet	Inflammation in paediatric asthma	effects observed after 6 months on 64 children's	Decreased inflammation of the airways in children with asthma		(Papamichael et al., 2019)
	Peri-operative oral n-3 PUFA supplementation (8–10 g for 2–5 days, then 2 g/day until discharge)	Reduction of the occurrence of post-operative atrial fibrillation	cardiac surgery received by 1516 patients	When compared to a placebo, n-3 PUFA delivery did not lower the incidence of post-operative atrial fibrillation.		(Tsoupras et al., 2022)
Cross-sectional study						
	Fish	Inflammatory indicators	3042 men and women	Related with lower inflammatory indicator levels	Even with less amounts of fish ingested; significant effects were obtained.	(Alhassan, Young, Lean, & Lara, 2017)
	Fish	Rheumatoid arthritis	176 participants	Reduced disease activity and cardiovascular disease risk in Rheumatoid arthritis patients		(Tedeschi et al., 2018)
Systematic review						
	Ingestion of fish and long chain n-3 PUFA	Menace of cerebrovascular disease	We examined aggregate data from 794,000 different people and 34,817 cerebrovascular outcomes from a total of 26 prospective cohort studies and 12 randomized controlled trials.	There are modest, inverse relationships between fish intake and long-chain omega-3 fatty acids and the risk of cerebrovascular issues. The positive impact of consuming fish on cerebrovascular risk is probably influenced by the interaction of various nutrients that are plentiful in fish.	Long chain n-3 PUFA, when assessed as circulating biomarkers in observational studies or through supplements in primary and secondary prevention trials, showed no association with cerebrovascular disease.	(Ma et al., 2021)
	Supplement of n-3 PUFA	Menace of major cardiovascular disease	68,680 participants were recruited in 20 studies—randomized trials—during 2012.	Insufficient evidence exists to indicate that n-3 PUFA supplementation has a positive impact on cardiovascular events	The supplementation of n-3 PUFA did not demonstrate a significant correlation with lowered risk for all-cause death, cardiac death, sudden death,	(Ma et al., 2021)

(*continued on next page*)

Table 5 (*continued*)

Study Design	Bioactive Lipid (Daily Dosage/ Amount in In Vivo Trials)	Reported effects	Models	Principal Impacts on Health	Further observations	Reference
				and other quantifiable health changes.	myocardial infarction, or stroke, as indicated by both relative and absolute measures of association.	
Other studies						
In the Alpha Omega experiment, a 2-by-2 factorial randomized control experiment, neither EPA/DHA nor ALA showed any discernible effects.	The interventions were 400 mg of EPA/DHA or 2 g of ALA.	Cardiovascular trials after myocardial infarction	4837 people who had myocardial infarction	There was no discernible positive impact for any of the n-3 PUFAs evaluated (EPA/ DHA or ALA).		(Kalstad et al., 2021)
Epidemiological study	n-3 PUFA	Consequence on inflammatory indicators	1123 patients	Consumption linked to decreased pro-inflammatory marker levels	Consumption linked to elevated anti-inflammatory marker levels	(Bersch-Ferreira et al., 2017)
Quantitative analysis	Fish	CHD mortality	8 studies	Decreased risk of CHD	There is a 3.9 % decrease for every extra dish per week.	(Zhang, Xiong, Cai, & Ma, 2020)

et al., 2019). Meta-analyses confirm cardiovascular benefits across marine lipid sources. Studies involving 7951 intervention individuals and 7855 control persons (1966–1999) showed decreased total death rate and reduced myocardial infarction from n-3 PUFA intake. Additionally, EPA+DHA supplementation > 2 g effectively lowers both systolic and diastolic blood pressure (Tsoupras et al., 2022). Shellfish contribute to cardiovascular health through their unique lipid profiles. With n-3 PUFA content ranging from 16.6 % to 57.1 % and favorable n-3/n-6 ratios > 1, shellfish provide cardiovascular benefits comparable to fatty fish, albeit in different concentrations (Aubourg et al., 2021).

6.3. Hepatoprotective

Marine lipids from diverse sources demonstrate hepatoprotective properties through multiple mechanisms, extending beyond traditional fish oil sources to include algae and other marine organisms. Fish oil hepatoprotection has been extensively documented. Multiple studies demonstrate that fish oil supplementation protects against drug-induced hepatotoxicity. Research on cod-derived fish oil showed protective effects against sodium nitrite-induced hepatotoxicity in rats. Fish oil supplementation notably improved acetaminophen-induced hepatic injury in rats. Additionally, fish oil demonstrated protective effects against isoniazid-rifampin induced hepatotoxicity (Basheer et al., 2017). Results accumulated indicate that fish oil demonstrated a beneficial therapeutic effect in hepatotoxicity. Marine-derived compounds show broader hepatoprotective potential. Marine lipids also play a role in anti-aging by preserving redox homeostasis, lowering oxidative stress, and regulating gene expression involved in cellular senescence and longevity (Pereira & Valado, 2023). These mechanisms contribute to hepatic protection through cellular preservation and antioxidant activities. Algae-derived compounds demonstrate anti-steatosis properties. While the current evidence focuses primarily on fish oil, emerging research suggests that marine microalgae produce bioactive lipids with hepatoprotective potential. The unique lipid compositions of microalgae, particularly their phospholipid and glycolipid content, may contribute to liver protection through anti-inflammatory and antioxidant mechanisms.

Maillard reaction products resulting from the combination of fish protein hydrolysates and ribose exhibit health benefits in terms of hepatoprotection (Yang, Lee et al., 2017; Yang, Du et al., 2017), expanding the scope of marine-derived hepatoprotective compounds beyond lipids alone. The molecular mechanisms underlying marine lipid hepatoprotection involve omega-3 fatty acids (EPA and DHA) and fat-soluble vitamins (D, E, and A), which collectively provide antioxidant and anti-inflammatory effects that protect hepatic tissue from various toxic insults (Yang, Lee et al., 2017; Yang, Du et al., 2017).

6.4. Other health benefits

Marine lipids from diverse sources provide numerous additional health benefits beyond cardiovascular and hepatic protection, including neuroprotection, skin health, wound healing, Marine lipids, especially omega-3 polyunsaturated fatty acids like EPA and DHA, have shown remarkable neuroprotective activity by promoting cognition development, improving neuroplasticity, and alleviating the risk and advancement of neurodegenerative disorders like Alzheimer's and Parkinson's through anti-inflammatory, antioxidant, and membrane-stabilizing activities (Bălașa et al., 2020; Naik et al., 2024). Marine lipids also play a role in anti-aging by preserving redox homeostasis, lowering oxidative stress, and regulating gene expression involved in cellular senescence and longevity (Pereira & Valado, 2023). In addition, omega-3-enriched marine oils play a crucial role in brain development, as studies indicate that DHA intake from diet enhances learning, memory, and neuronal development, particularly in childhood and the elderly (Pereira & Valado, 2023). Bioactive compounds derived from the marine environment have demonstrated antitumor activity by inhibiting inflammation, regulating immune responses, and triggering apoptosis in cancer cells (Andraka, Sharma, & Marchalant, 2020).

Skin health benefits extend across marine sources. Fish fatty acids have shown many benefits for the skin, such as strengthening the skin barrier, lowering inflammation from UV rays, decreasing hyperpigmentation, promoting wound healing, and easing dermatitis (Huang, Wang, Yang, Chou, & Fang, 2018). Marine-derived compounds from algae, particularly astaxanthin and other carotenoids, provide potent antioxidant protection for skin health. Fish oil supplementation has demonstrated effectiveness in improving skin hydration by reducing trans epidermal water loss, with significant changes observed beginning on day 60 in clinical studies. Wound healing acceleration involves multiple marine lipid sources. The omega-3 PUFAs found in various marine organisms exhibit significant effectiveness in addressing infections and promoting wound healing through anti-inflammatory mechanisms. Recent studies demonstrate that arginine and omega-3 PUFAs show considerable efficacy in wound management, with optimal dosages (3.5 % of total energy from omega-3 fatty acids) demonstrating significant impact on reducing wound-related infections (Abraúl et al., 2023).

Gut microbiota modulation represents an emerging area of marine lipid benefits. Strong evidence suggests that consuming marine lipids may change the composition of gut microbiota, potentially strengthen the immune system and reduce inflammatory illnesses. Omega-3 PUFAs supplementation enhances intestinal health by influencing the microbiota to generate anti-inflammatory molecules, including Short-Chain Fatty Acids (SCFAs) (Parolini, 2019). Galacto-oligosaccharide glycated fish peptides can be classified as prebiotics by enhancing total SCFAs production through beneficial bacterial population changes (Jin et al., 2018).

Anti-cancer and anti-aging properties have been documented across marine sources. Bioactive compounds derived from the marine environment have demonstrated antitumor activity by inhibiting inflammation, regulating immune responses, and triggering apoptosis in cancer cells (Andraka et al., 2020). The anti-aging properties of marine lipids work through preserving redox homeostasis, lowering oxidative stress, and regulating gene expression involved in cellular senescence and longevity.

Administration of omega-3 fatty acids in the form of fish oil has been proven to be safe. The dosage at which omega-3 fatty acids (3.5 % of total energy) demonstrated a significant impact on reducing infections related to wounds. The findings are obtained from both experimental animal models and studies involving humans (Aubourg et al., 2021). A recent study revealed that using snakehead fish extract spray on clean wounds resulted in significantly improved pain scores and cosmetic outcomes at weeks 2, 4, and 6 when compared to a placebo. The consumption of fish and its components plays a significant role in enhancing the wound healing process, primarily through the suppression of inflammation. Skin issues can result in significant complications for healthy skin, including cutaneous wounds, photoaging, various allergies, skin cancer, dermatitis, and melanogenesis. The use of fish oil has been demonstrated to be effective in addressing these issues (Chen, Jayachandran, Bai, & Xu, 2022). Fish contains a high concentration of PUFAs, which play a significant role in reducing cutaneous inflammation through their ability to counteract inflammatory arachidonic acid and inhibit the production of pro-inflammatory eicosanoids (Pereira & Cotas, 2023). The dietary supplementation of 18:3 PUFAs (GLA) has shown positive effects on dry skin and has been effective in preventing dermatitis. The constituents of fish oil, particularly the PUFAs, play a vital role in preserving skin homeostasis and improving skin abnormalities. Fish fatty acids have shown many benefits for the skin, such as strengthening the skin barrier, lowering inflammation from UV rays, decreasing hyperpigmentation, promoting wound healing, and easing dermatitis (Huang et al., 2018). In the acetone-induced dry skin rat model, a convincing study suggested that oral fish oil supplementation might reduce dryness and irritation. Fish oil supplements have been shown to improve skin hydration by reducing trans epidermal water loss. Significant changes were seen beginning on day 60. In the rat model, fish oil may also mitigate the acetone-induced alterations in the epidermal barrier. Additionally, there is strong evidence that eating fish may change the makeup of the gut microbiota, which might strengthen the immune system and reduce inflammatory illnesses. Omega-3 PUFAs supplementation may enhance intestinal health by influencing the microbiota to generate anti-inflammatory molecules, including Short-Chain Fatty Acids (SCFAs) (Parolini, 2019). Galacto-oligosaccharide glycated fish peptide can be classified as prebiotics by enhancing the total SCFAs through a reduction in the relative abundance of *Alloprevotella* and *Holdemanella*, while simultaneously increasing the relative abundance of *Anaerovibrio* and *Prevotella-9* (Jin et al., 2018). Additional studies on the advantages of fish or its components using metabonomics or metagenomics are essential.

7. Biotechnological applications of marine lipids

7.1. Nutraceuticals and functional foods

Marine lipids, especially omega-3 fatty acids sourced from fish and algae, are gaining recognition for their health advantages, resulting in their integration into nutraceuticals and functional foods (Fig. 4). Omega-3 fatty acids, including EPA and DHA, are linked to a variety of health advantages, such as promoting cardiovascular health, providing anti-inflammatory effects, and enhancing cognitive function. In accordance with these advantages, it is projected that merely 20 % of the worldwide population utilizes a sufficient amount of marine lipids essential for optimal health (Falch, 2023). Beyond omega-3s, marine lipids have other potential uses. The nutraceutical value of marine species is also impacted by a range of bioactive compounds, including as proteins, polysaccharides, and pigments. For instance, prebiotic properties and immune system modulation of polysaccharides derived from marine habitats, including fucoidans and carrageenans, are well known (Šimat et al., 2020). Furthermore, advanced techniques such as supercritical fluid extraction and enzymatic approaches, which seek to increase bioavailability and effectiveness in food items help to optimize lipid extraction. The marine nutraceuticals industry is expected to develop significantly; estimates suggest that it might reach $22 billion by 2025. Compounds produced from marine sources are becoming more well-known for their health benefits, which is driving their increase (Šimat et al., 2020). Modern lifestyles lead people to consume some highly caloric and unhealthy foods, which have caused a host of health problems, such as type 2 diabetes and heart disease. Marine lipids are a good source of high-value bioactive compounds which may be useful in fortifying human diets and obtaining higher nutritional levels, especially PUFAs in microalgae. Supplements containing PUFAs are used in health products, beverages, jam, pasta products and other daily foods that do not or have low levels of PUFAs. Fish products, which contain high-value fatty acids, can reduce the risk of some diseases by adjusting cholesterol and other indicators, as well as reduce the accumulation of toxins and heavy metals. Additionally, marine sources contain many other bioactive compounds, including proteins, minerals, and polysaccharides, each of which contributes to the increase of nutrients available for food production. Moreover, developments in food technology aim to preserve their nutritional integrity by including these lipids into various food matrices. Research on encapsulation methods is under growing focus in order to protect delicate marine lipids from oxidation all through processing and storage. A great chance to improve public health is presented by including marine lipids into functional foods and nutraceuticals. Realizing the full potential of these bioactive chemicals will depend on constant research into their extraction, stability, and use.

7.2. Pharmaceuticals

Different bioactive properties of marine lipids make them a valuable source for medical applications. From marine sources, the range of bioactive compounds collected includes fatty acids, antioxidants, and anti-inflammatory agents with possible relevance in treating many health problems (Kapoor et al., 2024). Particularly in relation to their effects on cardiovascular illnesses, depression, and inflammatory disorders, much research has been done on omega-3 fatty acids obtained from fish oils. Research has shown certain lipid-based molecules produced by marine life with antibacterial action. For example, certain phospholipids taken from fish have proven effectiveness against harmful bacteria and fungus. Additionally, bioactive peptides obtained from marine proteins are being explored for their possible uses in drug development, due to their ability to affect biological processes at the cellular level (Mutanda, Naidoo, Bwapwa, & Anandraj, 2020). The pharmaceutical industry is increasingly recognizing the potential of microalgae as a source of bioactive lipids. Microalgal species possess the ability to produce high-value metabolites that serve as precursors for

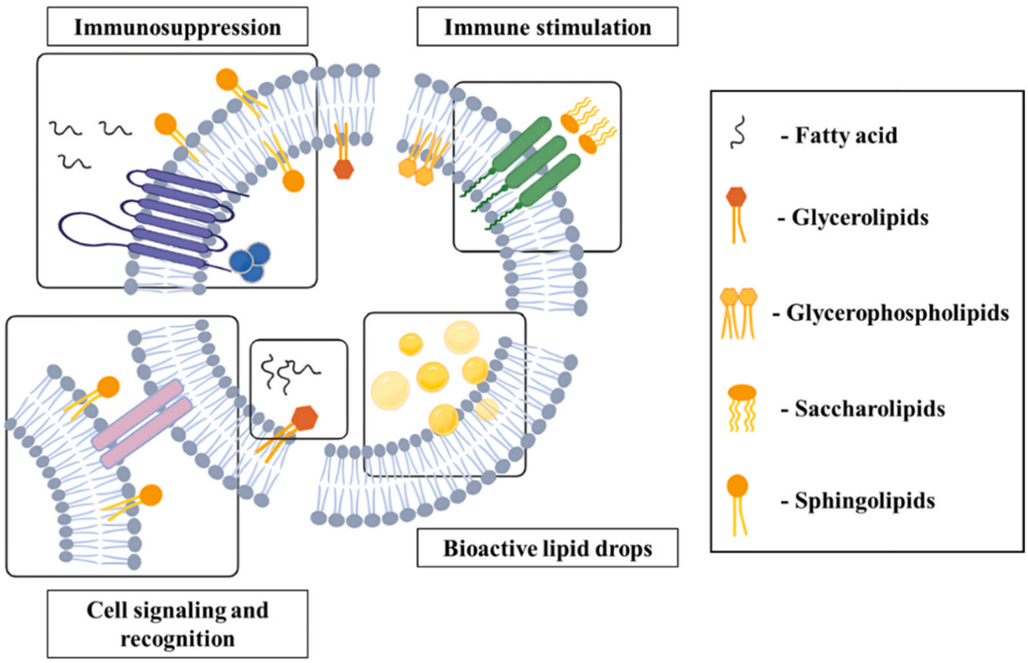


Fig. 4. Marine lipids crucial roles in cell structure, energy storage, and signaling, with significant biomedical applications in human medicine.

pharmaceuticals. For instance, biotechnological methods can be employed to modify the lipid composition of microalgae, enhancing the production of specific fatty acids or other bioactive compounds (Kapoor et al., 2024). Moreover, progress in the study of cellular lipid profiles is aiding in the discovery of new lipid-based pharmaceuticals sourced from marine environments. This area presents opportunities for discovering innovative therapeutic agents that can more accurately target particular diseases in contrast to traditional pharmaceuticals. The integration of marine lipids into pharmaceutical development presents a multifaceted opportunity for innovation in drug formulation and therapeutic interventions.

7.3. Cosmetics and personal care

Marine lipids have become more and more popular in the cosmetics sector because of their positive effects on skin health. Known for their

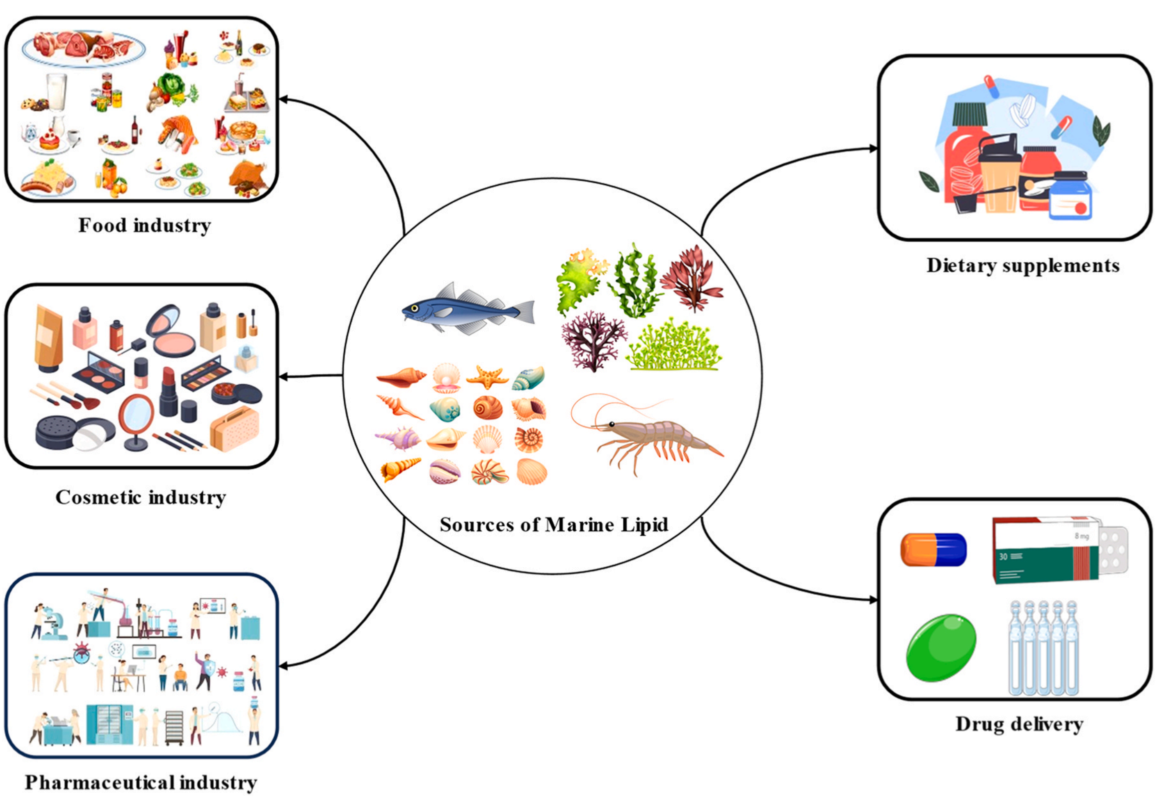


Fig. 5. Industrial applications of marine lipids in food, cosmetics, pharmaceuticals, and dietary supplements.

moisturizing, anti-aging, and anti-inflammatory properties are marine-derived components like omega-3 fatty acids, phospholipids, and antioxidants. These lipids aid to enhance moisture levels and preserve skin barrier integrity, therefore slowing down indications of aging. Microalgae are a particularly interesting source of components for cosmetic products (Thiyagarasaiyar, Goh, Jeon, & Yow, 2020). Their capacity to generate many lipid forms, including glycolipids and sphingolipids, makes them useful for developing skin care treatments. Algal oils high in omega-3s, for example, are used in creams and serums meant to increase skin suppleness and lower inflammation (De Luca et al., 2021). Astaxanthin and other marine-derived antioxidants have also become a bit known for their strong free radical scavenging power. Because astaxanthin shields skin cells from oxidative stress generated by UV exposure, it is sometimes used into anti-aging treatments (Ahmad & Ahsan, 2020). Moreover, the biodegradability of marine lipids fits the rising consumer desire for eco-friendly cosmetic goods. Natural marine sources may provide a competitive advantage in the market as customers get more aware of the components in personal care products.

7.4. Other industrial applications

Beyond food and medicine, marine lipids have great promise for a range of industrial uses (Fig. 5). Biofuels is one prominent field, because of their high lipid content, microalgae are being investigated as sustainable sources of biodiesel (Jabłońska-Trypuć et al., 2023). These lipids may be converted into biodiesel, which helps lessen dependency on fossil fuels and support renewable energy sources. Additionally, marine lipids are used to make bioplastics. Lipid-based compounds may be added to polymers to increase their biodegradability while preserving their desired mechanical qualities. This supports international initiatives to reduce plastic waste and advance circular economy principles (Cheah et al., 2023). Marine lipids are being researched for usage in animal feed formulations in addition to energy uses (Table 6). Adding omega-3-rich fish or algae oils to feed may improve its nutritional composition and help cattle develop more quickly and stay healthier overall.

Additionally, more effective extraction techniques for separating valuable lipids from unexploited marine resources have been made possible by developments in biotechnology. By reducing waste in the seafood sector, this not only optimizes resource use but also promotes (Monteiro et al., 2024). Overall, the wide range of industrial uses for marine lipids demonstrates their adaptability as sustainable resources that may support environmental preservation while satisfying financial demands.

8. Challenges and future perspectives for food applications

8.1. Sustainability challenges in food applications

The sustainable production and utilization of marine lipids for food applications face multiple interconnected challenges that require innovative solutions and comprehensive planning. Sustainable sourcing strategies are critical for the long-term viability of marine lipid food applications. Traditional fish-based sources face sustainability concerns due to overfishing pressures. Fish farming offers a practical way to lessen the overfishing of consumable fish globally, but it has serious environmental repercussions for the production of aquafeed, which is mostly made from wild fish. More sustainable approaches include developing aquafeed recipes that incorporate land-based ingredients and reducing dependency on wild-caught fish for feed production.

Microalgae represent the most promising sustainable alternative for food applications. Since they don't need freshwater or arable land and may accumulate large amounts of fatty acids under unfavourable circumstances, microalgae and microalgae-like protists seem to be a feasible and sustainable source of EPA, DHA, and other FAs. The Food and Drug Administration has approved several species of microalgae and microalgal oil, demonstrating their safety profiles for food applications (Adarme-Vega et al., 2012). However, large-scale development still requires optimization of growth conditions for algae cultivation and VLC-PUFA accumulation, as well as improvement of harvesting and extraction methods.

Table 6
Biotechnological applications on marine lipids.

Industry	Application	Example/ Product	References
Nutraceuticals	Supplemental omega-3 EPA/ DHA for heart and brain health	EPAX Novus Lipid (EPA/ DHA, Cetoleic 10)	(Hayes, 2023)
	Fish collagen and algae extracts for anti-inflammation & skin health	Gummies, tablets with fish collagen	(Lim, 2025)
Food	Omega-3 and fish protein fortification of snacks, cereals, and health beverages	Omega-3 fortified cereals and beverages	
	Clean-label, plant-based omega-3 oils derived from microalgae	Algal oil-enriched plant-based foods	(Hayes, 2023)
Pharmaceuticals	Targeted medication delivery using lipid-based nanocarriers (e. g., cancer, neurology)	Lipid nanoparticles in mRNA vaccines, liposomal doxorubicin (Doxil)	(Khodaverdi et al., 2022)
	Omega-3-based medications for mental and cardiovascular health	Prescription EPA/DHA (e. g., Vascepa)	(Arutyunov, Arutyunov, Ageev, & Fofanova, 2021; Candido et al., 2023)
Cosmetics	Marine-derived collagen, peptides, and omega-3 fatty acids are used in anti-aging, hydrating, and skin-rejuvenating creams.	Marine collagen creams, astaxanthin serums	(Khajure & Rasal, 2024)
	Formulations that restore the skin barrier and reduce inflammation	Seaweed/ fucoidan-based moisturizers	
Other Industries	Sports nutrition: snacks and drinks with omega-3 fatty acids and protein hydrolysates	Marine protein hydrolysate shakes	(Kostrakiewicz-Gierałt, 2024)
	Microalgal triglycerides as Biofuels	Algal biodiesel	(Khajure & Rasal, 2024)

Production scalability challenges remain significant for food applications. Almost all lipids from microalgae are currently generated under heterotrophic conditions that are prone to contamination. Future research focuses on producing autotrophic microalgae on a large scale, which would be highly sustainable if nutrients were recovered through fermentation of algal biomass after oil extraction. This approach would require fertilizer input but offers a circular economy model for sustainable production. Economic viability represents a major challenge for widespread food application. The development of large-scale downstream processes that are both economically viable and environmentally friendly remains essential. Focus on minimizing production losses and energy expenses linked to extraction and purification processes is crucial for making marine lipids cost-competitive with conventional food ingredients. Advances in synthetic biology and microbial biotechnology offer promising alternatives for sustainable omega-3 production. Engineered microalgae, yeast, and bacteria are being developed to biosynthesize long-chain polyunsaturated fatty acids such as EPA and DHA under controlled conditions, independent of marine ecosystems. This approach not only reduces ecological impact but also ensures consistent quality and scalability for nutraceutical and pharmaceutical applications. Integration of these technologies with circular bioeconomy principles could redefine the future of marine lipid production, balancing innovation, sustainability, and global health needs.

8.2. Climate change impact on marine food lipids

The availability and quality of marine lipid resources are expected to be influenced by climate change and associated shifts in ocean ecosystems. Rising sea temperatures, ocean acidification, and altered nutrient dynamics may change lipid biosynthesis pathways in marine species, leading to variations in fatty acid profiles and overall productivity. These environmental pressures highlight the importance of adaptive resource management and continuous monitoring of lipid yield and composition in wild and aquaculture species.(Cooley et al., 2023). Climate change impacts ecosystems with unprecedented physical and chemical changes, which individually and collectively affect all marine species (Bartley et al., 2019). Canada's waters are warming and losing pH, particularly in the Arctic, which affects both the quantity and quality of marine lipids available for food production (Grant, MacDonald, Benner, Michielsens, & Latham, 2019). Temperature effects on marine food webs significantly impact lipid composition and availability. Temperature has a big effect on the food chain structure of marine ecosystems in the northern hemisphere. These effects can be observed both directly and indirectly, with potential exacerbation from simultaneous pH decreases (Ullah, Nagelkerken, Goldenberg, & Fordham, 2018). Ocean acidification affects planktonic systems, benthic environments, and deep-sea ecosystems, all of which contribute to the marine food web that produces valuable lipids. Fatty acid profile alterations due to climate change directly impact food applications (Borgå et al., 2022). Research on diatoms and copepods revealed that in acidified marine systems, both organisms and their food sources contained more saturated fatty acids and fewer PUFAs. This change in fatty acid composition directly affects the nutritional value of marine lipids for food applications, as PUFAs are the primary target compounds for human nutrition (Doney, Busch, Cooley, & Kroeker, 2020). Ecosystem disruption affects lipid transport and quality. Climate change alters the amount, composition, and movement of lipids in marine organisms and ecosystems, affecting energy flow and the transport of lipid-soluble compounds. These impacts include the movement of carbon generated from phytoplankton to the deep ocean, mediated by zooplankton, which influences both local marine productivity and global carbon cycles (Brun et al., 2025).

8.3. Future food applications and market trends

The integration of marine lipids into food systems represents a significant opportunity to address global nutritional challenges while supporting sustainable food production. Addressing modern dietary challenges through marine lipid fortification offers substantial potential. Modern lifestyles lead people to consume some highly caloric and unhealthy foods, which have caused a host of health problems, such as type 2 diabetes and heart disease. Marine lipids are a good source of high-value bioactive compounds which may be useful in fortifying human diets and obtaining higher nutritional levels, especially PUFAs in microalgae (Maltsev & Maltseva, 2021). The global recognition that only 20 % of the worldwide population consumes sufficient marine lipids for optimal health indicates enormous market potential (Falch, 2023).

Functional food development represents a rapidly expanding market opportunity. Marine lipids are increasingly being incorporated into various food matrices including supplements, beverages, jam, pasta products, and other daily foods that naturally contain low levels of PUFAs. The development of omega-3 fortified cereals, plant-based foods enriched with algal oils, and clean-label products derived from microalgae demonstrates the versatility of marine lipids in food applications. Market growth projections indicate substantial expansion potential. The marine nutraceuticals industry is expected to reach $22 billion by 2025, driven by increasing recognition of marine-derived compounds' health benefits (Šimat et al., 2020). This growth is supported by consumer awareness of the benefits of omega-3 fatty acids and the development of sustainable production methods. Regulatory approval and safety considerations continue to advance, facilitating market expansion. The FDA approval of various microalgae species and microalgal oils demonstrates regulatory acceptance of alternative marine lipid sources for food applications. This regulatory support enables broader commercial development and consumer acceptance of marine lipid-fortified foods.

8.4. Technological innovations for food integration

Advanced technologies are crucial for successfully integrating marine lipids into food systems while maintaining their nutritional integrity and sensory acceptability. Encapsulation technologies are critical for protecting marine lipids during food processing and storage. Research on encapsulation methods is under growing focus in order to protect delicate marine lipids from oxidation all through processing and storage. These technologies enable the incorporation of sensitive omega-3 fatty acids into various food matrices without compromising their nutritional value or creating off-flavours. Advanced extraction and purification methods are improving both yield and quality of marine lipids for food applications. The development of supercritical fluid extraction, enzymatic methods, and ultrasonic-assisted extraction focuses on enhancing efficiency and sustainability through reduced organic solvent usage. These methods provide higher purity and yield of marine lipids while maintaining their bioactive properties. Food matrix optimization ensures successful integration of marine lipids into diverse food products. Advances in food technology focus on preserving nutritional integrity while incorporating marine lipids into various food matrices. This includes developing delivery systems that mask fishy flavours, prevent oxidation, and maintain stability throughout product shelf life. Recovery and circular economy approaches are essential for sustainable marine lipid utilization. Future initiatives should focus on compound recovery using cutting-edge technologies such as ultrafiltration, minimizing production losses, and developing alternative methods for purifying biomass generated by microalgae species. The establishment of circular economy principles in marine lipid production supports both environmental sustainability and economic viability. Quality assurance and safety evaluation remain priorities for food applications. Further investigation is necessary to enhance understanding of the digestion, absorption, and metabolism of supplemented ω-3 LC-PUFAs within the human body. Additionally, research should focus on assessing the suitability and safety of derived DHA/EPA from microalgae in food products, identifying and evaluating suitable food matrices for enrichment such as fitness bars, oil capsules, yogurt drinks, and butter. The future of marine lipids in food applications depends on successfully addressing these technological challenges while maintaining focus on sustainability, safety, and nutritional efficacy. Continued innovation in extraction methods, processing technologies, and food integration strategies will be essential for realizing the full potential of marine lipids in addressing global nutritional needs.

9. Conclusion

Marine lipids represent a valuable resource with numerous applications in biotechnology, pharmaceuticals, and nutrition. These lipids, derived from sources such as fish and microalgae, are recognized for their health benefits, particularly due to their elevated levels of omega-3 fatty acids, including EPA and DHA. Their significance in promoting health is underscored by their capacity to reduce food allergies, alleviate gut dysbiosis, and consequently diminish inflammation. The extraction of marine lipids is evolving through the combination of innovative methods and traditional techniques. While contemporary techniques such as supercritical fluid extraction and ultrasonic-assisted extraction focus on enhancing efficiency and sustainability through reduced organic solvent usage, traditional methods like Soxhlet extraction continue to hold significance. The future course of marine lipids will be shaped by sustainable sources and optimal applications moving forward. Microalgae are gaining recognition as a promising alternative to fish-based sources, aligning with the demand for sustainable practices. Enhancing the therapeutic potential of specific lipid compounds specific for various health disorders relies on continuous exploration of their bioactivity. Marine lipids are set to play an increasingly significant role in enhancing human health and addressing global health challenges. As this review provides an insight on their sources, extraction methods, biotechnological, industrial applications and the sustainable sources for the better future. Although significant progress has been made in understanding the sources, extraction methods, and functional applications of marine lipids, some limitations persist within the current literature. Many studies remain species-specific or geographically limited, with variable methodologies that complicate direct comparison. Furthermore, large-scale industrial validation and long-term clinical studies assessing bioavailability and health outcomes of novel lipid sources are still limited. Future research should focus on developing standardized extraction protocols, improving lipidomic profiling tools, and strengthening sustainability assessments of emerging marine lipid sources. Integration of multi-omics approaches and life-cycle analysis will be crucial for translating laboratory findings into practical, eco-friendly solutions for the food and pharmaceutical industries.

CRediT authorship contribution statement

Yuvaraj Dinakarkumar: Writing – review & editing, Conceptualization. **Aishwarya Lakshmi Thasvanth Raj:** Writing – original draft. **Rinish Mortin John:** Writing – original draft, Software. **Muthezhilan Radhakrishnan:** Visualization. **Nadeem Siddiqui:** Resources. **Arokiyaraj Selvaraj:** Validation. **S Ivo Romauld:** Writing – review & editing.

Author contribution

Yuvaraj: Conceptualization, Reviewing and Editing**; Rinish:** Software and writing- original draft**; Aishwarya:** Writing- Original draft preparation**; Romauld:** Editing**, Arokiyaraj:** Validation**; Nadeem:** Review and resources; **Muthezhilan:** Visualizaion

Consent to Publish

All the authors have given their content to publish this research

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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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