From Krill to Whale: an overview of marine fatty acids and lipid compositions

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Abstract: *In this study, fatty acid compositions of phyto-zooplankton (calanoid copepod species, krill…) to fish species (mackerel, sardine anchovy, salmon, shark) are presented. Marine oils are essentially used for their high long-chain polyunsaturated fatty acids (LC-PUFA), namely eicosapentaenoic (EPA) and docosahexaenoic (DHA) for their good health impact. Due to health benefits of the omega-3, weekly fish consumption is today recommended by many authorities (FDA, AFSSA…). Capture fisheries and aquaculture supplied the world with about 110 million tonnes of food fish in 2006 (FAO 2009), providing an apparent per capita supply of 16.7 kg. It is well established that the lipid composition of fish muscle is influenced by the diet and also depends on the effects of environmental factors (temperature, oxygen concentration in sea water) and endogenous medium (physiological state and individual variability). In general, cultured fish have been reported to have a softer texture than wild fish, which has been related to the differences in muscle structure, proximate composition and nutritional value. New applications of typical compounds (wax esters, squalene …) or lipid classes (glycerophospholipids, ether glycerolipids, sphingophospholipids …) as cosmetics, functional foods and dietary supplements will become very important in the near future with nano-structured drug carriers in pharmaceutical and biomedical areas.*

Key words: *fatty acids compositions, long-chain polyunsaturated fatty acids (LC-PUFA), EPA, DHA, Krill, fish roes, sharks*

In this study, the variety of lipid classes and fatty acid compositions from phyto-zooplankton to marine mammals and fish will be overviewed. In fact, the composition of this energy resource changes all along the animal food chain and now it has a growing interest for human consumption and for the pharmaceutical and nutraceutical industries.

Since prehistoric times, marine oils have been mainly used as an illuminant in lamps and as lubricants. Their medicinal virtues have been pointed out in the middle of the 19th century. However, it was only with the publication of the Danish Epidemiological studies of Bang and Dyerberg in the early 1970s that the true worth of the research on polyunsaturated fatty acids (PUFAs) has been understood. They postulated that the low incidence of coronary heart disease of Greenland Eskimos might be related to their distinctive dietary habit and use of lipids rich in PUFAs. From this milestone, considerable evidence from epidemiological, clinical and biochemical benefits of n-3 LC-PUFAs, mainly eicosapentaenoic (EPA) and docosahexaenoic (DHA) acids, was shown. These PUFAs exert a strong positive influence on human health, preventing the risk of cardiovascular diseases, several immune disorders affecting neural development and neurodegenerative diseases, and they protect against tumorigenesis. For these reasons, regular fish consumption to provide approximately 200-500 mg per week of EPA and DHA has been recommended by different health organizations. Consequently, these studies led to a strong demand of fish oils and fish oil concentrates on supplement and functional food markets. The need is now so important that the natural resource is declining, leading to the development of aquaculture with the consequence that farmed fish being fed with regular diets, their lipid composition is notably different from wild species, which varies all year long. It is well established that the lipid composition of fish muscle is influenced by the diet and also depends on the effects of environmental factors (temperature and oxygen concentration in sea water) and endogenous medium (physiological state and individual variability). As well known, lipid-rich tissues contain triacylglycerols (TAG) as major lipids, while tissues low in lipid content may be dominated by polar lipids such as phospholipids (PL).

To date, most of the marine living organisms have been investigated for their lipid composition. However, few studies on lipids sources such as PL, glycolipids, alkylglycerols, etc., which may have potentially many benefits over "simple" TAG from fish oils, are undertaken. Several studies on non-conventional marine sources with high contents of LC-PUFAs (microalgae, krill, fish roes…) are now underway.

The purpose of this article is to present an overview of the lipid composition throughout the marine food chain, from the planktonic communities of the world ocean, the large predators, the marine mammals and the world of marine aquaculture.

Lipids from marine sources: structure and composition

The oceans and adjacent seas have a complex food web including planktivorous and herbivores (krill, salps, copepods) fed upon by birds, fish, squid, seals and baleen whales. Lipids are essential biochemical constituents of all organisms, and lipid composition can often be related to physiology, taxonomy, and can be used to understand and identify food web interactions. Marine oils are much more complex in chemical structure than other oils or fats. They contain many classes of lipids (TAG, PL, hydrocarbons, wax esters, ether-linked compounds…) as well as the diverse group of fatty acids ranging from saturated to highly polyunsaturated. The

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carbon chain length in marine oil fatty acids contain 20, 22 and to a limited extent, 24 carbon atoms, with several double bonds. There are more than 50 different fatty acids present in typical fish oils.

LC-PUFA with 5 and 6 double bonds, namely EPA (C20:5n-3, EPA) and DHA (C22:6n-3, DHA) range in proportion of total fatty acids from 15% to 30% in marine oils. Nearly, all the PUFA of marine oils ranging in chain length from C18-C22 are of n-3 with the linolenic acid (LA) as precursor. *Figure 1* depicts the chemical structure of polyunsaturated fatty acids, which are usually investigated for their health benefits. Another unusual feature of marine oils is the presence of relatively large amounts of odd carbon chain (mostly C15, C17, C19) and branched fatty acids. Marine oils also contain unsaponifiable matter which varies largely with the species. The presence of sterols is also present in great quantity in fish roes, shellfish and crustaceans. The amount of cholesterol present in fish is lower (under 100 mg/100 g wet fish) than in shellfish and crustaceans (usually 150-200 mg/100 g) (Stansby, 1969).

Fatty acids proportion of any given marine species is not constant from fish to fish, but varies depending upon the feed consumed by the fish as well as some other factors (geographical area, season, water temperature, type of feed…).

Omega-3 long-chain fatty acids originate in the lipids of phytoplankton passed up the food chain through zooplankton to the fish. Linoleic acid (18:2) and Linolenic acid (18:3) are considered as essential fatty acids (FA), because they are necessary in the diet for good health and cannot be synthesized by the human organism. Moreover, they are the precursors of LC-PUFA, in particular EPA and DHA. However, a relatively small amount of the precursor (α-linolenic acid) can be converted into EPA and even less to DHA (Hjaltason, 2006).

The beneficial effect of fish consumption on human health has been related, among other factors to the high content of LC-PUFA, which plays very important roles in many aspects of human health disorders, in particular in reducing risks of cardiovascular diseases, hypertension, allergies, and are essential for brain and retina development. The effect of these FA, namely EPA and DHA, is well documented in numerous investigations, as were reviewed (Simopoulos, 1991; Horrocks and Yeo, 1999; Riediger *et al.*, 2009) since the original epidemiological investigations carried out by Bang and Dyerberg (1972) in Eskimos. The consumption of EPA and DHA increased because of the consumer's awareness on health benefits of the omega-3 fatty acids. Capture fisheries and aquaculture supplied the world with about 110 million tonnes of food fish in 2006 (Data from FAO fisheries and aquaculture 2009) providing an apparent per capita supply of 16.7 kg (live weight equivalent), which is among the highest on record *(table 1)*.

The natural molecular forms of PUFA are typically TAG and PL. Fatty acid composition and volatile flavour compounds of nine commercial marine oils used in aquaculture have been analyzed by Giogios *et al.* (2009). This study presents the similarities and differences in FA composition of various oils and the variability of the volatile compounds.

Table 1. *World fisheries and aquaculture production and utilization (FAO Fisheries and Aquaculture 2009).*

	2002	**2003**	**2004**	**2005**	**2006**
Production					
INLAND					
Capture	8.7	9.0	8.9	9.7	10.1
Aquaculture	24.0	25.5	27.8	29.6	31.6
Total inland	32.7	34.4	36.7	39.3	41.7
MARINE					
Capture	84.5	81.5	85.7	84.5	81.9
Aquaculture	16.4	17.2	18.1	18.9	20.1
Total marine	100.9	98.7	103.8	103.4	102.2
TOTAL CAPTURE	93.2	90.5	94.6	94.2	92.0
TOTAL AQUACULTURE	40.4	42.7	45.9	48.5	51.7
TOTAL WORLD FISHERIES	133.6	133.2	140.5	142.7	143.6
UTILIZATION					
Human composition	100.7	103.4	104.5	107.1	110.4
Non-food uses	32.9	29.8	36.0	35.6	33.3
Population (billions)	6.3	6.4	6.4	6.5	6.6
Per capita food fish supply (kg)	16.0	16.3	16.2	16.4	16.7

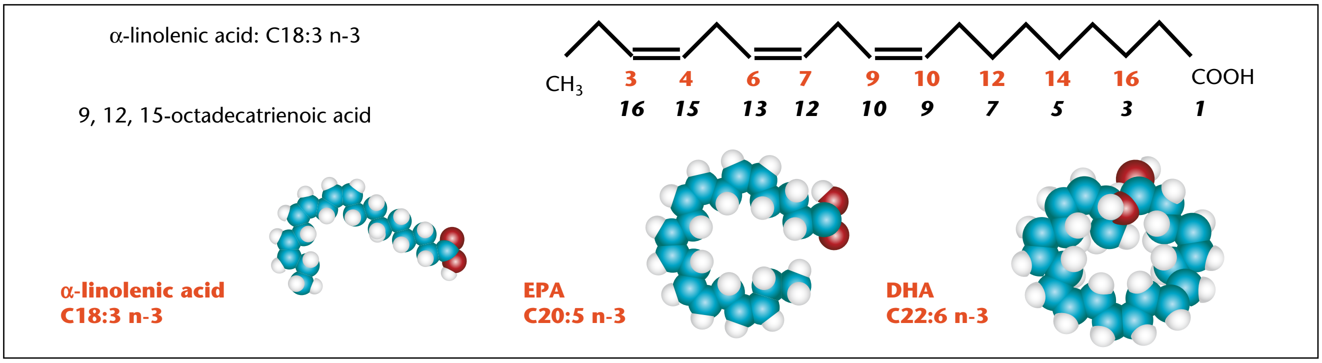

Figure 1. *Structure of the precursor (linoleic acid) and long chain polyunsaturated fatty acids (acid eicosapentaenoic EPA C20:5n-3; acid docosahexaenoic DHA C22:6n-3).*

In fish, LC-PUFAs are mainly located in the *sn*-2 position of the TAG, while saturated fatty acids and monounsaturated fatty acids are located primarily in the *sn*-1 and *sn*-3 position (Ackman, 1980).

Saturated fatty acids (14:0, 16:0 and 18:0) were preferentially esterified in both *sn*-1 and *sn*-3 positions, whereas LC-PUFAs were preferentially located in the *sn*-2 position (Aursand *et al.*, 1995; Ando *et al.*, 1996; Aubourg *et al.*, 1996; Nwosu and Boyd, 1997; Aursand *et al.*, 2000). It is interesting that in the TAG lipids of marine mammals (whale, seal), the *sn*-2 position is more enriched in saturated fatty acids and LC-PUFA is more located in *sn*-1 and *sn*-3 position (Brockerhoff *et al.*, 1967; Ackman, 1980).

While TAG is quite homogeneous group of lipids, PL can be divided into three classes: glycerophospholipids, ether glycerolipids and sphingophospholipids. Glycerophospholipids represent the most widespread PL class and can be divided into subclasses according to their polar head, the phosphatidylcholine (PC) is the predominant one.

PL in fish constitute an important source of health beneficial *n*-3 PUFA (Takahashi, 2004; Falch *et al.*, 2006). Higher levels of EPA and DHA are concentrated in the PL compared to TAG (Al-Sayed Mahmoud *et al.*, 2008; Belhaj *et al.*, 2010).

Furthermore, use of polar lipids as carriers of *n*-3 PUFAs has received interest, because EPA and DHA in the *sn*-2 positions are more readily absorbed compared to the TAG, where these fatty acids are in one of the other positions in the molecule (Takahashi, 2004).

Lipids in oceanic zooplankton: a role of feed biomarkers

Planktonic organisms are characterized by their limited mobility, largely prohibiting a self-determined movement against the prevailing ocean currents over longer temporal and spatial scales (Hagen and Auel, 2001). Biodiversity in biomass and plankton abundance are closely related with the seasonal oscillation, light intensity, temperature and depth. The herbivorous organisms, the calanoid copepod species and krill (*Euphausiacea*), synthesize large amount of wax esters with long-chain monounsaturated fatty acids (C22) and alcohols as high-efficiency energy reserve *(table 2)*. Plankton accumulates lipid reserves as wax esters, in order to withstand long periods of starvation and to provide the buoyancy in the water column. There is general agreement that phytoplanktons are the major source of essential fatty acids in the marine environment and the ratio of typical fatty acids can be used as biomarkers for different classes of phytoplanktons (Alkanani *et al.*, 2007). Specific trophic biomarkers, typical of phytoplankton or zooplankton, have been used because of their incorporation without modification into neutral lipid of the predator. For instance, fatty acids such as C16:1 (n-7) or EPA are typical markers of diatoms, whereas DHA or C18:4 (n-3) occurs in dinoflagellates. Copepod species are targeted by C20:1 and C22:1 fatty acids.

Smaller phytoplankton species such as pennate diatoms and flagellates contain significant amounts of LC-PUFA, especially EPA and DHA, as well as 16:0, 16:1ω7, 14:0 and the diatom marker 16:4ω1 (Parrish *et al.*, 1991). Larger phytoplankton such as dinoflagellates also contain EPA and DHA, 18:4ω3 and 16:0, as well as the uncommon 18:5ω3 fatty acids (Leblond and Chapman, 2000). *Table 3* showed the FA composition of phytoplankton with high amounts of 16:0, 22:6ω3, 20:5ω3, 14:0, 16:1ω7 and 18:0, but usually high percentages of 18:1ω9 and C20-NMIDs (non-methylene-interrupted dienoic). This 20:2NMIDs fatty acid group may have an important metabolic or structural function. The pathways for the biosynthesis of these fatty acids in molluscs have been established and involved the insertion of a double bond at the 5th position to form 20:2-5,13 and 20:2-5,11.

As in phytoplankton, PUFA was the major component of the identified fatty acids in mussels. The role of PUFA may be important in many different development stages of mussels due to their limited ability to synthesize 20:5ω3 and 22:6ω3 (Alkanani *et al.*, 2007).

The biomass of Antarctic krill is the most abundant animal species on Earth and paradoxically, one of the least exploited marine resources in the world (the standing stock biomass is estimated: 650 million metric tonnes). An estimated 150 million metric tonnes per year were consumed by birds, fish, squid, seals and baleen whales (Watkins, 2007). *E. superba* provides 30%-90% of the diet for these carnivores (Phleger *et al.*, 1998). Among 85 different species of small planktonic crustaceans known

Table 3. *Fatty acid composition (%) in phytoplankton from Fortune Harbour and Charles Arms sites (adapted from Alkanani* et al.*, 2007).*

Fatty acid	**Phytoplankton**
14:0	7.41
i15:0	1.17
15:0	1.45
16:0	24.67
16:1n-7	5.05
18:0	4.57
18:1n-9	4.87
18:1n-7	2.90
18:2n-6	1.42
18:3n-3	1.27
18:4n-3	2.24
20:1n-11	0.23
20:1n-9	1.56
20:2NMID	0.57
22:2NMID	0.11
20:4n-6	0.64
20:5n-3	9.28
22:5n-3	0.41
22:6n-3	14.97

NMID FA: Non-Methylene-Interrupted Dienoic FA.

Table 2. *Lipid data of several calanoid copepod from the Antarctic Weddell Sea (modified after Hagen and Auel, 2001). DM: dry mass.*

Characteristics	***Calanoides acutus***	***Rhincalanus gigas***	***Calanus propinquus***	***Metridia gerlachei***	***Pareuchaeta antarctica***
Maximum size (mm)	5	8	5	4	9
Maximum lipid content	51% DM	33% DM	56% DM	44% DM	45% DM
Major storage lipid	Wax esters	Wax esters	triacylglycerols	Wax esters/triacylglycerols	Wax esters
Typical fatty acids	20:1; 22:1	16:1; 18:1; 18:4	22:1 (2 isomers)	16:1; 18:1	16:1; 18:1
Typical fatty alcohols	20:1; 22:1	14:0; 16:0	—	14:0; 16:0	14:0; 16:0

as euphausiids, six species have been fished and they have a potential commercial interest. The "Antarctic krill" *Euphausia superba*, a species contributing essentially to the biomass in Antarctic waters, is subject to significant commercial fishing. Krill oil is gaining increasing attention from nutraceutical and functional food due to its three main quality attributes: the omega-3 fatty acids as well as PL. It is also a rich source of astaxanthin, carotenoid pigment and powerful antioxidant. *E. superba*, *E. tricantha* and *E. frigid* were also characterized by relatively high percentage of TAG with high level of PUFA. This lipid class also appears as the major energy storage in several Antarctic copepods, which could represent potential diets (Ju and Harvey, 2004). EPA and DHA were the two major unsaturated fatty acids *(table 5)*. TAG is the main lipid deposits, but polar lipids such as PL, namely phosphatidylcholine, are also accumulated. PL were the major lipid class in most of the zooplankton *(tables 4, 6)*. Hagen *et al.* (1996) have suggested that even PL also might serve as storage lipids for *E. superba* and *E. crystallorophias*. Moreover, *Euphausia crystallorophias* and *Thysanoessa macrura*, in contrast to *E. superba*, synthesize primarily wax ester as energy reserve (Hagen and Auel, 2001). Even though a diverse suite of sterols were present, cholesterol remained the major sterol (more than 76% of total sterols) in all krill, with a minor variation between species (Phleger *et al.*, 1998; Ju and Harvey, 2004). Moreover, krill contains potent proteolytic and lipolytic enzymes, and high levels of free fatty acids can occur where sufficient care is not taken in handling and processing samples.

Zooplankton biomass represents the favourite diet of whales which can swallow up to 4 tonnes of krill per day. These microscopic crustaceans provide a significant crude lipid source for these marine mammals required during migrations. Budge *et al.* (2008) have studied the blubber fatty acid composition of bowhead whales (*Balaena mysticetus*) to evaluate the implications for diet assessment and ecosystem monitoring. FA compositions of bowhead whales were characterized by typical marine FA, and were dominated by 14:0, 16:0, 16:1n-7, 18:0, 18:1n-9, 18:1n-7, 20:1n-11, 20:1n-9, 22:1n-11, 22:1n-9, 20:5n-3, 22:5n-3 and 22:6n-3, which depend on the phytoplankton fatty acid signature *(table 7)*. Whale oil derived from the blubber is typically low in omega-3 LC-PUFA. Several studies (in Budge *et al.* article, 2008) showed that vertical stratification of FA composition in blubber has been reported. A higher monounsaturated FA amount (14:1n-5, 16:1n-7, 18:1n-9) and lower saturated FA (16:0, 18:0) were observed in the outer in contrast to the inner blubber layers. This particular arrangement of FA might enhance membrane fluidity in the outer blubber layers and improves the insulation properties of the blubber. Moreover, researches focus on the potential to use bowhead blubber FA to monitor ecological change at the base of the food web that is driven by climate variation.

Several studies have investigated the relationship between lipid content/fatty acid compositions and season of catch. Zlatanos and Laskaridis (2007) have studied the influence of seasonality on the fat content and the fatty acid composition of the sardine (*Sardina pilchardus*), the anchovy (*Engraulis encrasicholus*) and the picarel (*Spicara smaris*), in order to find the best source of n-3 fatty acids during the year. *Table 8* adapted from the aforementioned authors showed that fish lipid content depends on season, fish life cycle, external factors like temperature, salinity and fatty acid composition of their food. The fat content of the sardine was minimal at the end of winter and maximal at the end of spring. On the other hand, the fat content of the anchovy and the picarel was maximal at the end of winter – beginning of spring and minimal at the end of the summer.

Jensen *et al.* (2007) have studied the variations of fatty acid composition of herring (especially the variation in EPA and DHA) on a large

Table 4. *Composition of lipid classes from Southern Ocean zooplankton (adapted from Phleger* et al.*, 1998).*

	TAG	**FFA**	**Sterols**	**PL**	**Lipids mg/g**
E. superba	37.3	0.0	4.1	58.2	29.5
E. tricantha	54.2	1.0	1.0	36.3	3.2
E. frigida	27.2	0.7	3.1	69.1	15.8

Table 5. *Composition of fatty acids (% of total fatty acid) in Antarctic Euphausiids (adapted from Ju and Harvey, 2004).*

Fatty acids	***Euphausia superba***	***Euphausia tricantha***	***Euphaudia frigida***
14:0	1.2	0.6	0.9
16:0	16.2	13.4	18.0
16:1n-7	1.3	1.5	2.2
18:0	1.2	5.6	5.9
18:1n-9	5.9	17.7	15.3
18:1n-7	8.0	10.5	12.9
18:2n-6	0.6	1.8	2.2
20:1n-9	0.3	9.5	3.1
20:5n-3	31.6	6.7	10.9
22:6n-3	28.3	15.8	18.1

Table 6. *Lipid data of the dominant Euphausiid species in the Antarctic (modified after Hagen and Auel, 2001) DM: dry mass.*

Characteristics	***Euphausia superba***	***Euphausia crystallorophias***	***Thysanoessa macrura***
Maximum size (mm)	56	41	33
Maximum lipid content	46% DM	52% DM	56% DM
Major storage lipid	Triacylglycerols phosphatidylcholine	Wax esters phosphatidylcholine	Wax esters phosphatidylcholine
Typical fatty acids	14:0; 16:0; 18:1	16:0; 18:1	14:0; 16:0; 18:1
Typical fatty alcohols	none	14:0; 16:0	18:1; 20:1

Table 7. *Variation of fatty acid proportions in blubber layers in bowhead Whales* Balaena mysticetus *(adapted from Budge* et al.*, 2008).*

Fatty acids	Inner	outer
10:0	0.36	0.08
14:0[a]	4.34	4.13
i-15:0	0.12	0.12
15:0	0.24	0.23
16:0[a]	11.30	8.89
i-17:0	0.12	0.10
17:0	0.15	0.11
18:0[a]	2.91	1.69
Subtotal	19.55	15.35
14:1n-9	0.27	0.14
14:1n-5[a]	0.19	0.63
16:1n-11	0.37	0.40
16:1n-9	0.22	0.23
16:1n-7[a]	13.75	19.31
17:1n-8	0.13	0.20
18:1n-11	2.38	2.05
18:1n-9[a]	11.63	13.24
18:1n-7[a]	4.10	5.32
18:1n-5	0.60	0.58
20:1n-11	2.69	2.14
20:1n-9[a]	11.19	8.42
20:1n-7	1.72	1.34
22:1n-11[a]	5.00	5.67
22:1n-9	1.5	1.07
22:1n-7	0.31	0.27
24:1n-9	0.19	0.10
Subtotal	56.24	61.13
16:3n-6	0.61	0.73
16:3n-4	0.24	0.20
16:4n-1	0.35	0.29
18:2n-6	0.69	0.66
18:2n-4	0.13	0.17
18:3n-6	0.15	0.12
18:3n-4	0.25	0.27
18:3n-3	0.31	0.34
18:4n-3	0.82	0.65
18:4n-1	0.35	0.43
20:2n-6	0.15	0.17
20:4n-6	0.30	0.32
20:4n-3	0.44	0.43
20:5n-3[a]	7.40	9.40
21:5n-3	0.44	0.34
22:5n-3[a]	3.68	3.03
22:6n-3[a]	6.19	4.30
Subtotal	22.49	21.86

[a] Indicates FA used to assess extent of stratification.

numbers of individuals caught. The lipid content and the fatty acid composition of the different catches summed up for PUFA, MUFA and SFA are shown in *figure 2*. Total lipid content varied significantly among catches, with the highest amount during summer for herring. The seasonal variation in lipids is ascribed to the lack of feeding during the winter. This high EPA content found only in herring caught in May 2003 is related to variation in the fatty acid composition of the copepods on which the herring feed.

However, these seasonal lipid variation affects not only fish species with greater richness in oil considered traditionally to be “blue” (fatty), but also the fish species commonly considered to be “white” (little fat). Soriguer *et al.* (1997a) have investigated the composition in lipids of 35 common fish species in Spain *(table 9)*. The conclusions of this study showed important differences in fat concentration of the species studied.

It is therefore very important from a nutritional point of view to take into account the lipid content and the fatty acid composition which may influence the quality and functional properties of the processed products. Soriguer *et al.* (1997b) reported the extreme case of the mackerel (*S. scombrus*) which, between spring and winter, may increase its lipid composition eight folds in percentage terms.

Fish species like sardine, anchovy and mackerel are rich sources of LC-PUFA, and therefore, they are recommended as part of a diet aiming at improving the intake of these fatty acids (Zlatanos and Laskaridis, 2007; Jensen *et al.*, 2007). Although, the recommended intake varies with the different associations (American Heart Association, Food and Drug Administration, International Society for the Study of Fatty Acids and Lipids), most recommendations are in the range of 0.5-1.0 g EPA + DHA day^{-1} for adults (250 mg DHA and 250 mg EPA day^{-1} according to AFSSA, 2010). A survey of the nutritional composition of fish and seafood purchased and consumed by French population was conducted by Sirot *et al.* (2008). A total of 159 fish, mollusc and crustacean samples were collected in four French coastal areas and analyzed for total lipids and fatty acids, especially n-3 LC-PUFA. Results showed that eel, salmon, swordfish and halibut are the richest fish in total lipids and n-3 LC-PUFA, with average levels of 20.4, 13.5, 12.4 and 11.7 g lipids/100 g fresh edible portion, respectively.

In the world, the ten species that contributed most to global catches represent more than 30% of the total global marine catch in 2006 *(figure 3)*. This group of species consists of five small pelagic species (anchoveta, Atlantic herring, chub, Chilean jack mackerels and Japanese anchovy), two tunas (skipjack and yellowfin), two low-value gadiformes (Alaska pollock and blue whiting) that are mostly marketed in processed forms, and the large-head hairtail, a bentho-pelagic species (FAO Fisheries and Aquaculture, 2009).

We observe a considerable variation of fatty acid composition of fish oils between different fish species. *Table 10* and *table 11* showed the fatty acid composition of several investigated fish species with low and high amount of PUFA (data adapted from numerous authors).

It is well established for various fish species that the fatty acid composition is influenced by variations in the feed available for the species, water temperature, sexual status, size or age of animals affecting metabolic activity (Médale, 2009; Robin *et al.*, 2003). However, the use of vegetable oils in fish diets has an influence on flesh quality and considering the interest in fish n-3 fatty acids for human health, fatty acid pro-

Table 8. *Fat contents (g/100 g dry sample) of sardine (*Sardina pilchardus*), anchovy (*Engraulis encrasicholus*) and the picarel (*Spicara smaris*) (data adapted from Zlatanos and Laskaridis, 2007).*

	February	April	June	August	October	December	Mean
Sardine	3.88 ± 0.2	11.86 ± 0.6	11.47 ± 0.5	5.88 ± 0.2	8.46 ± 0.5	6.92 ± 0.2	8.08
Anchovy	5.71 ± 0.4	3.41 ± 0.3	1.32 ± 0.2	0.94 ± 0.2	2.99 ± 0.3	2.85 ± 0.2	2.87
Picarel	4.42 ± 0.4	4.52 ± 0.3	2.95 ± 0.2	0.93 ± 0.2	1.85 ± 0.3	3.06 ± 0.3	2.96

Catch	Number of herring	PUFA		Lipid
		EPA	DHA	
NSE-Jul-01	26	6.9 ± 0.2	11.0 ± 0.4	16.0 ± 0.9
S-Jul-01	193	6.5 ± 0.1	10.0 ± 0.1	16.9 ± 0.3
K-Jul-01	33	6.8 ± 0.3	11.0 ± 0.5	14.0 ± 0.9
NSW-Aug-01	61	6.1 ± 0.2	10.6 ± 0.2	15.6 ± 0.5
BS-Nov-01	58	6.1 ± 0.1	10.9 ± 0.1	12.7 ± 0.3
BS-Mar-02	56	5.1 ± 0.1	9.6 ± 0.2	9.5 ± 0.4
NSE-Jun-02	39	7.0 ± 0.2	11.5 ± 0.5	12.9 ± 0.8
NSE-Jul-02	19	7.8 ± 0.4	13.8 ± 1.3	9.6 ± 1.1
S-Jul-02	157	6.4 ± 0.1	10.3 ± 0.2	14.6 ± 0.3
K-Jul-02	40	6.4 ± 0.1	10.0 ± 0.2	15.4 ± 0.5
NSW-Sep-02	57	5.8 ± 0.1	10.2 ± 0.2	10.1 ± 0.4
NSN-Nov-02	50	5.4 ± 0.1	11.0 ± 0.4	6.5 ± 0.4
NSN-Feb-03	50	4.4 ± 0.2	13.1 ± 0.6	4.5 ± 0.3
K-Feb-03	50	4.5 ± 0.1	9.5 ± 0.4	7.9 ± 0.4
NSN-May-03	48	11.0 ± 0.3	11.9 ± 0.3	6.9 ± 0.3

Figure 2. *Fatty acid composition of herring (*Clupea harengus *L.): influence of time and place of catch on n-3 PUFA content (adapted from Jensen* et al.*, 2007).*

file of fish fed plant oils might be considered as having possible negative effects in this regard. Despite the "washout" period to return to values similar to those of fish continuously fed, several studies showed that some differences still remained among experimental groups (Polvi and Ackman, 1992; Robin *et al.*, 2003; Nanton *et al.*, 2007). The functional nutritional value of these modified products is thereby reduced, linking alternative lipids with reductions in the nutritional benefit of consuming fillets from cultured fish. To mitigate conflicting demands of sustainability and product value, the implementation of "finishing diets" at the end of the production cycle to restore LC-PUFA content was used leading to a partial restoration of fillet LC-PUFA content (Lane *et al.*, 2006).

In general, cultured fish have been reported to have a softer texture and milder flavour than wild fish, which has been related to differences in muscle structure, proximate composition and the aromatic compounds profile (Fuentes *et al.*, 2010). They investigated the chemical composition, nutritional value and physicochemical parameters of sea bass (*D. labrax*) from different geographical areas of Spain and from aquaculture and wild origin.

The saturated fatty acids and polyunsaturated fatty acids were higher in wild sea bass, whereas farmed specimens showed a higher content of monounsaturated fatty acids. Sea bass can be considered as a good source of the n-3 series fatty acids, particularly of EPA and DHA, showing the highest levels in wild specimens *(table 12)*. Moreover, higher fat levels in farmed fish (4.4/100 g) compared to wild fish (1 g/100 g) have also been observed due to the use of commercial diets usually higher in fat content and more reduced activity for the cultured fish (Fuentes *et al.*, 2010).

Capture fisheries and aquaculture supplied the world with about 110 million tonnes of food fish (FAO Fisheries and Aquaculture, 2009). Of this total, aquaculture accounted for 47% and more than 110 million tonnes (77%) of world fish production was used for direct human consumption in 2006. Most industrial fish oil is now used in aquaculture as part of the feed for farmed fish, with close to 85% of production consumed by the sector, and with salmonids responsible for more than 55% of the sector's share (FAO, 2009). Demand for fish oil for direct human use is boosting prices. In early 2008, fish oil prices soared to an all-time record of US$1 700/tonne, compared with US$915/tonne one year earlier (FAO, 2009).

The aquaculture sector consumed about 3.06 million tonnes (or 56.0%) of world fishmeal production and 0.78 million tonnes (or 87.0%) of total fish oil production in 2006, where more than 50% goes into salmonid diets. Other fishery products used in the production of aquafeeds are krill meal, squid meal, squid liver powder, squid oil, shrimp meal and crab meal. The total amount of fishmeal and fish oil used in aquafeeds is estimated to have grown more than three folds between 1992 and 2006 (The State of World Fisheries and Aquaculture, 2008, FAO Fisheries and Aquaculture, 2009).

Table 9. *« Blue » or « White » fish species: a lipid composition depending on the seasons (adapted from Soriguer* et al.*, 1997).*

Name	Lipids (in g/100 of wet muscle tissue)	n-3 (%)	n-6 (%)
Dover sole	0.7-1.8	21.5-34.6	3.8-5.4
Turbot	0.7-1.1	35.1-39.2	4.0-4.2
Tuna	0.9-1.4	13.0-35.6	3.8-4.5
Anchovy	2.6-4.3	35.6-43.3	2.6-3.3
Mackerel	**1.8-17.2**	14.4-38.3	2.7-4.9
European eel	8.4-9.0	7.8-9.5	7.3-7.9
Bass	0.6-3.0	20.2-30.0	2.8-3.9
Shrimp	0.5-1.0	26.0-35.5	6.1-12.8

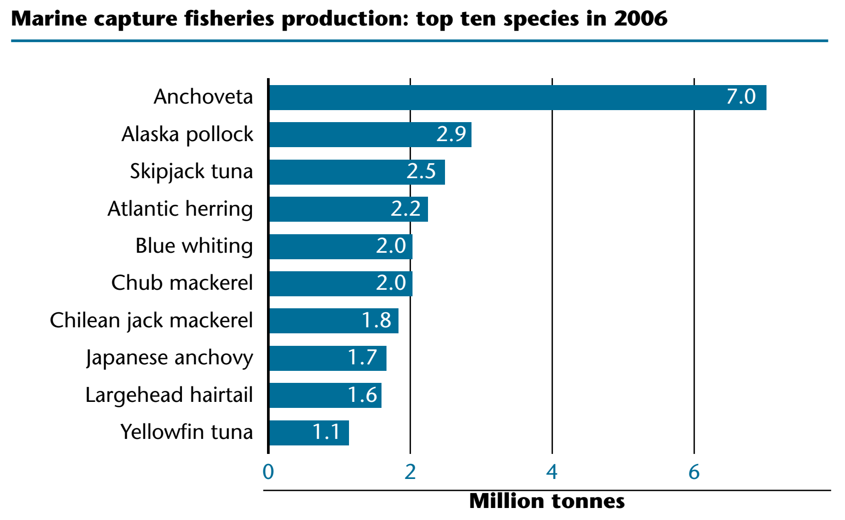

Figure 3. *The State of World Fisheries and Aquaculture 2008 (FAO Fisheries and Aquaculture, 2009).*

Table 10. *Fatty acid composition of several investigated fish species adapted from different source.*

Fatty acids	Turbot (Psetta maxima) (a)	Menhaden (b)	Mackerel (c)	Mackerel (d)	Herring (mean value) (e)	menhaden (f)	*Seal (c)*	*Whale muscle (c)*
14:0	6.9	11.3	5.1	5.3	6.2	7.6	5.0	2.6
15:0	–	0.7	–	0.6	–	0.6	–	
16:0	14.4	21.3	12.6	19.4	11.6	19.2	11.3	15.3
16:1n-7		12.6	8.1	4.5	3.8	10.4	–	5.7
18:0	1.5	3.5	2.6	4.9	1.0	3.54	1.1	5.7
18:1n-9	5.9	10.4	12.3	13.9	7.2	12.3	22.3	38.8
18:1n-7	2.6		–	–	1.3	–	4.9	4.0
18:2n-6	5.3	1.5	1.5	1.9	1.6	1.3	1.1	1.1
18:3n-3	1.2	1.4	1.1	2.3	1.3	1.2	–	–
18:4n-3	2.2	3.3	2.0	–	3.5	2.3	–	–
20:1n-9	9.2	1.0	7.2	4.4	12.5	2.0	–	6.1
20:4n-6	0.4	1.3	–	1.7	–	2.1	–	–
20:5n-3	6.8	14.1	6.1	8.7	6.3	12.0	6.6	0.9
22:1n-11	11.3	–	–	–	21.5	–	2.3	2.2
22:5n-3	1.8	2.8	–	1.3	–	3.0	4.4	0.7
22:6n-3	11.1	14.4	7.0	15.9	10.6	8.4	8.7	

a) Robin *et al.* (2003); b) Lyberg and Adlercreutz P. (2008); c) Sébédio *et al.* (1993); d) Soriguer *et al.* (1997a,b); e) Jensen *et al.* (2007); f) Liu *et al.* (2004).

Due to the general decline of fish stocks, the investigation of unfished or less-exploited fish species is needed, and a better use of raw material is required, involving the evaluation of by-products from fisheries. Vall Ould El Kebir *et al.* (2007) investigated the complete fatty acid composition from some Elasmobranchs species which seems to be still neglected, such as rays. It is well known that the liver of ray fishes is rich in poly and highly unsaturated fatty acids. Ray fish liver oil may have applications in aquacultural feed manufacturing and other industries, taking into account that over 6,000 tonnes of ray fishes are caught in Mexico each year (Perez-Velazquez, 2008). *Table 13* adapted from Vall Ould El Kebir *et al.* (2007) showed the high amounts of essential PUFA, specially DHA in muscle, liver and gonad of rays which can be used for direct human nutrition or the food processing industry.

Fish oil may also be extracted from salmon heads, rich in LC-PUFA, by enzymatic process and could be used in nutraceutical domain due to the high level of polar lipids (Linder *et al.*, 2005; Belhaj *et al.*, 2010).

Considerable data are available on lipids and fatty acid compositions in shark tissues, mainly centered on liver oil, which contained high levels of DHA (Navarro-Garcıa *et al.*, 2000) *(table 14)*. The liver oil of many deep-sea sharks contains several uncommon, low-density lipid classes, chiefly squalene (density 0.86 g mL^{-1}) and diacyl glyceryl ether (density 0.89 g m^{-1}) participating in the buoyancy of the animal (Wetherbee and Nichols, 2000). The incorporation of squalene hydrogenated into squalane in pharmaceutical products enhances skin absorption of cosmetics and medicaments. Studies on pelagic shark species revealed that the liver lipids contained high levels of n-3 PUFA, especially DHA (up to 25%). Depending on the shark species, the oil can be rich in 1-*O*-alkylglycerols, which exhibit bacteriostatic and fungistatic properties, anti-inflammatory activities and a hemopoietic effect (Navarro-Garcia *et al.*, 2000).

Fish eggs: a source of LC-PUFAs

For their nutritional and sensorial values, fish roe products are widely consumed throughout the world and can be considered as an interesting valuable source of PUFA. Many studies have highlighted the extreme variability of fish roe's composition in water, protein and lipid content due to several factors like fish species, developmental stage, environment, season and diets (Al-Sayed Mahmoud *et al.*, 2008). Roe yield (wt%) differs from fish species to another; it can be ranged from 6% in mackerel fish (*Scomber japonicus*), 10% in chinook salmon (*Oncorhynchus tshawytscha*), 20% in white sturgeon (*Acipenser transmontanus*), up to 26% in carp (*Cyprinus sp.*). The physicochemical composition of salted and dried mullet roes (*Mugil cephalus)* known as "bottarga" was investigated by Scano *et al.* (2008).

An average lipid content of 270 mg/g of the edible portion for bottarga sample was measured. Total cholesterol was measured as mean content of 9.3 and 10.5 mg/g of edible product and represented ca. 3%-4% of total lipids. Cholesterol content of *Oncorhynchus mykiss* roe was about 3.5% of total lipids, compared to higher contents observed in white seabream (*Diplodus sargus*) 11.4%, cod (*Gadus morhua*) 8.7%, atlantic salmon (*S. salar*) 5.2%, and herring (*Clupea harengus*) 8.3%. However, oil egg may be extracted by enzymatic process and contained about half of the total cholesterol amount, due to the tension-active properties of polar lipids partially retained in the heavy fraction (Al-Sayed Mahmoud *et al.*, 2008). The composition of fatty acids present in the bottarga product is

Table 11. *Fatty acid composition of several investigated fish species adapted from different source.*

Fatty acids	***Sardina Pilchardus* *(a)***	***Anchovy (Engraulis encrasicholus)* *(a)***	***Tuna* *(c)***	***Pacific bluefin tuna* *(d)***	**Squid oil (e)**	**Crude sardine oil (f)**
14:0	7.0	6.8	3.9	2.9	5.7	6.34
15:0	0.9	1.1		0.4	0.6	–
16:0	23.2	27.1	17.6	17.8	22.8	22.2
16:1n-7	6.1	4.2	5.4	3.7	4.2	9.58
18:0	3.3	5.2	4.1	6.2	1.7	4.06
18:1n-9	7.1	8.5	12.4	15.5	17.2	5.23
18:1n-7	2.3	1.3	3.5		–	–
18:2n-6	1.5	1.8	1.9	1.0	1.7	1.03
18:3n-3	2.0	1.5	–	1.2	1.0	0.57
18:4n-3	0.8	0.6	–	–	3.6	
20:1n-9	1.2	1.7	–	0.3	4.4	2.87
20:4n-6	1.2	0.7	–	1.3	1.0	0.28
20:5n-3	10.7	7.8	12.4	6.9	12.4	28.2
22:1n-11	0.8	0.5	0.5	–	–	–
22:5n-3	1.1	0.6	1.7	0.8	0.7	–
22:6n-3	20.8	21.1	27.8	23.3	19.1	16.7

a) Zlatanos and Laskaridis (2007); c) Ackman (2006); d) Nakamura *et al.* (2007); e) Lyberg and Adlercreutz (2008); f) Okada and Morrissey (2007).

Table 12. *Comparison of wild and cultured sea bass (Dicentrarchus labrax) quality (adapted from Fuentes* et al.*, 2010).*

Fatty acids (%)	**Farmed wild sea bass (Greece)**	**Farmed wild sea bass (Spain)**	**Wild sea bass**
14:0	3.35	3.27	2.08
15:0	0.73	0.59	0.92
16:0	21.50	22.24	24.57
17:0	0.29	0.24	0.50
18:0	4.51	4.58	9.31
16:1n-7	4.19	4.58	5.12
18:1n-9	28.27	27.96	16.47
20:1n-9	4.01	5.66	1.95
18:2n-6	13.56	9.91	2.73
18:3n-3	1.15	1.19	1.13
20:2n-6	1.98	2.10	1.06
20:4n-6	0.33	0.48	5.37
20:5n-3	7.81	9.29	12.17
22:6n-3	8.33	7.36	16.62

shown in *table 15* and expressed as percentage of total fatty acids. They showed a concentration of approximately 16%-18% of saturated fatty acids (mainly 16:0), 35% of MUFA (mainly 16:1 *n*-7 and 18:1 *n*-9) and 34%-37% of PUFA. The total content of the *n*-3 derivatives EPA and DHA amounted to ca. 21% for the mullet eggs (Scano *et al.*, 2008) and 31% for the trout roes (Al-Sayed Mahmoud *et al.*, 2008). The most common salmon roe products are ikura (salted individual eggs) and suijko (salted cured whole skeins), which are produced mainly from chum salmon (*Oncorhynchus keta*) and pink salmon (*Oncorhynchus gorbuscha*).

Bekhit *et al.* (2009) have studied the physicochemical properties of chinook salmon and their impact on the maturity. Fish oils play an important role in providing the energy required by the eggs during development. Palmitic acid (16:0) was the dominant saturated fatty acid in salmon roe. Similarly, oleic acid was the most abundant monounstaturated fatty acid. EPA and DHA are the dominant polyunsaturated fatty acids with 6.8% and 24.3% of total fatty acid composition, respectively. However, maturity had no effect on the percentage of the fatty acids. Lipids

Table 13. *Fatty acids composition from liver and muscle of three Mauritanian rays (adapted from Vall Ould El Kebir* et al. *2007).*

Fatty acids	**Dasyatis marmorata**		**Rhinobatos cemiculus**	
	Muscle	**Liver**	**Muscle**	**Liver**
14:0	2.24	5.77	5.83	0.05
15:0	0.29	0.18	0.43	0.12
16:0	19.4	14.10	21.0	20.7
i-17:0	0.98	0.32	0.73	0.37
ai-17:0	0.22	0.37	0.45	0.06
17:0	0.18	0.27	0.41	0.19
18:0	9.23	5.51	13.3	19.4
20:0	0.21	0.11	0.13	0.23
22:0	0.42	–	0.60	–
16:1n-10	0.34	0.58	0.28	0.24
16:1n-7	2.85	11.6	1.90	9.42
16:1n-6	0.53	0.66	0.8	0.59
17:1n-11	0.68	0.11	0.26	0.87
17:1n-8	0.30	1.14	0.44	0.99
18:1n-12	1.48	1.18	1.81	0.13
18:1n-9	8.61	6.59	8.00	6.54
18:1n-7	3.49	5.63	0.44	0.35
20:1n-10	0.18	–	0.46	–
20:1n-9	0.50	1.02	0.21	0.61
20:1n-7	0.15	1.30	0.63	0.60
Diunsaturated fatty acids				
18:2 Δ9,12	1.09	1.08	0.40	0.39
20:2 Δ7,15	0.80	1.86	0.43	1.30
22:2 Δ6,14	0.19	–	0.23	–
22:2 Δ7,13	3.46	2.20	2.28	1.94
22:2 Δ7,15	3.46	–	0.35	–
16:3n-4	0.56	1.04	0.53	0.53
18:4n-3	0.67	1.15	0.68	0.81
18:3n-6	0.10	0.95	0.75	0.87
20:5n-3	4.95	3.41	4.63	5.01
20:4n-6	5.57	5.66	7.32	6.63
22:4n-6		1.40	–	1.00
22:5n-3	9.37	5.24	3.91	4.76
22:6n-3	16.10	13.4	18.70	13.2

Table 14. *Fatty acid composition of liver oil of pelagic shark species of* Carcharhinus falciformis *from the Gulf of California and Caribbean waters (adapted from Navarro-Garcia* et al.*, 2000).*

Fatty acids	**Fatty acid profile (weight percentage of total fatty acids)**
14:0	3.03
14:1	0.97
16:0	22.79
16:1	3.48
17:0	1.44
17:1	0.66
18:0	8.42
18:1n-9	10.98
18:1n-7	2.85
18:2	1.33
18:3	3.16
20:2	0.66
20:4	2.29
20:5	5.14
24:1	0.52
22:6	25.05

Table 15. *Fatty acid composition of different source of fish roes (adapted from different authors).*

Fatty acid	**Chinook salmon roe (*Oncorhynchus tshawytscha*) (a)**	**Pacific salmon roe (*Oncorhynchus keta*) (b)**	**Trout roe (*Oncorhynchus mykiss*) (c)**	**cod (G. Morhua) (d)**	**mullet roe (Mugil cephalus) (e)**
14:0	1.54	3.19	3.0	2.4	2.07
15:0	0.35	0.56	0.2	–	0.44
16:0	11.65	11.53	16.1	17.9	10.90
16:1n-7	4.54	5.45	6.2	3.7	17.92
18:0	4.32	3.60	5.1	1.3	3.18
18:1 n-7	3.25	2.44	4.3	13.0	7.22
18:1n-9	22.33	16.21	15.6	2.7	10.61
18:2n-6	3.42	1.59	4.2	0.8	1.27
18:3n-3	0.6	1.20	1.1	0.5	0.57
20:4n-6	2.40	1.37	1.3	1.4	1.69
20:5n-3	6.86	16.33	11.5	14.6	9.40
22:5n-5	3.85	4.37	4.8	1.3	5.95
22:6n-3	24.32	16.87	24.0	29.5	11.62

from spawning cod (*G. morhua*) roes were studied by Falch *et al.* (2006a) and results showed that more than 40% of the fatty acids were *n*-3 fatty acids. The polyunsaturated fatty acids made up nearly half of the amount of fatty acids and are comparable to what has recently been found in gonads of cod species (Falch *et al.*, 2006b).

Conclusion

The standing stock of phytoplankton and zooplankton biomass represents the first link in the marine food chain for birds, fish, squid, seals and baleen whales. The fatty acids diversity (saturated, mono and polyunsaturated) esterified on TAG or on polar lipids classes of oil and fats appears as high energy reserve or provide buoyancy function (krill and deep-sea sharks). Marine oils are characterized by a high amount of long chain polyunsaturated n-3 fatty acids, namely EPA and DHA, which have considerable impacts on health. Since the epidemiological studies conducted by Bang and Dyerberg (1972), consumption of fish oil increases significantly due to the beneficial effects of these fatty acids related in numerous studies. During the 1980s, lipids researches focused on the beneficial EPA effects on heart and inflammatory diseases. And in 1990s, health beneficial effects of the DHA were found – the neonatal development, brain development and eyesight. Today, cognitive decline in the elderly is a major healthcare concern, and effects of these PUFAs, mainly the DHA were explored to treat or delay the onset of the Alzheimer's disease (AD) (Cunnane *et al.*, 2009). Weekly fish consumption is today recommended by many authorities, and world fish captures steadily grow (FAO, 2009). However, fish species stock will not be sufficient to answer consumer's demand. In addition, aquaculture production is playing an increasing role in satisfying demand for human consumption of fish and fishery products. The consumption rose from 14% in 1986, to 30% in 1996 and to 47% in 2006, and it can be expected to reach 50% in the next few years (FAO, 2009). In farmed fish, artificial diets provide a wide range of nutrients, which not only determine fish growth rate but also flesh composition in particular the lipid content, which may be quantitatively and qualitatively modified. Sustainable expansion of aquaculture requires the use of alternative lipid sources e.g. vegetable oils, but modified feed formulations may alter the final fatty acid composition, mainly the LC-PUFA content of cultured products, and limit their nutritional value to human consumers.

In recent year, marine PL with the high content of LC-PUFA represent a potential EPA and DHA source for human consumption. Today, there are no rich sources on marine-based PL. Small commercial production of these lipids was extracted from krill, fish roes, salmon heads and squid. These polar lipids were commonly used in formulas for fish larvae in aquaculture. PL applications as functional foods, dietary supplements will become very important in the near future with nano-structured drug carriers in pharmaceutical and biomedical areas.

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