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Effects of food processing on the lipid nutritional quality of commercially important fish and shellfish

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ABSTRACT

Fish and shellfish are important sources of high quality lipids, especially omega-3 long-chain polyunsaturated fatty acids. In most countries, seafood is eaten cooked to eliminate any potential parasites and pathogens. In addition, cold storage plays an important role in extending the shelf life of seafood. However, both cooking and storage processes can cause alterations in the lipid content and fatty acid profile of fish and shellfish. Although the lipid nutritional quality of fish and shellfish have recently been reviewed, these reviews mainly focus on raw seafood, and information on the impact of food processing on the lipid nutritional quality of fish and shellfish still lacks coherence. Therefore, this study was carried out to provides a critical reviews on the effects of food processing, especially cooking and cold storge, on the lipid nutritional quality of fish and shellfish. Overall, from the perspective of lipid nutritional quality, baking and steaming are the most recommended cooking methods for fish and shellfish, respectively, while it is strongly not recommended to fry seafood with margarine. For cold storage, 3 days and 2 weeks are the most recommended storage periods for refrigeration and frozen storage, respectively. This article can provides consumers with useful information to choose food preparation and storage methods based on their personal interest in specific lipid nutritional quality indicators.

1. Introduction

Fish and shellfish are important sources of high quality animal protein, very rich in omega-3 long-chain polyunsaturated fatty acids (n-3 LC-PUFA) (e.g. Bienkiewicz, Tokarczyk, & Biernacka, 2022; Tan, Liu, & Zhang, 2021; Tan, Zhang, Li, Ma, & Zheng, 2021; Tan & Zheng, 2022) and bioactive compounds such as carotenoids (Tan et al., 2022) and polysaccharides (Tan et al., 2023a), with well-established beneficial properties for human health. Among these nutrients, n-3 LC-PUFAs, especially eicosapentaenoic acid (EPA, 20:5n-3) and docosahexaenoic (DHA, 22:6n-3), have been shown to play a critical role in various stages of life, from eye and brain development in fetuses and infants to cancer prevention, cardiovascular protection, neurological development and cognitive development in adults and elderly (e.g. Arnett et al., 2019; Li et al., 2021; Mohan et al., 2021).

In general, the dietary guidelines for n-3 LC-PUFA vary depending on health organizations and research groups (Li et al., 2021; Tan et al., 2023c). Despite that, many health organizations and research groups recommend a minimum daily n-3 LC-PUFA intake of 500 mg/ day or at least two servings of seafood per week (e.g. Israel Heart Society, 2011; Vannice and Rasmussen, 2014). However, only population in a few regions, including Scandinavia, Japan and areas with indigenous populations, meet this recommended level (Stark et al., 2016). In fact, over 80 % of the world's population has a daily intake of n-3 LC-PUFA that is less than half of the recommended daily intake (Stark et al., 2016).

Recently, scientists have found that global warming has reduced the production of n-3 LC-PUFA in primary producers (phytoplankton) and reduced the availability of n-3 LC-PUFA transfer to grazing food webs (Tan et al., 2022), indirectly reducing the availability of n-3 LC-PUFA for human consumption (Colombo et al., 2020; Tan et al., 2023b). According to model simulations, Colombo et al. (2020) predicted that by 2100, the amount of DHA available to humans will decrease by 10 to 58 %, and in the worst scenario, 96 % of the global population may have insufficient DHA intake. As a results, many studies have been carried out

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to increase the production of n-3 LC-PUFA form seafood and identifying alternative source of n-3 LC-PUFA (e.g. Tocher et al., 2019; Barta et al., 2021).

In addition to increasing the supply of n-3 LC-PUFA, reducing the loss of n-3 LC-PUFA during food processing (cold storage and cooking) is equality important for improving the availability of n-3 LC-PUFA to consumers. On the one hand, cooking refers to the heat treatment process that can eliminate pathogens from food (e.g. Sardenne et al., 2021; Tenyang et al., 2022; Biandolino et al., 2023). On the other hand, cold storage (refrigeration and freezing) plays an important role in extending the lifespan of food (e.g. Sardenne et al., 2021; Bienkiewicz et al., 2022; Lian et al., 2022), respectively. However, heat treatment during cooking and long period cold storage may cause modification in lipid profile, and affect the lipid nutritional quality of seafood (e.g. Tenyang et al., 2022; Lian et al., 2022; Biandolino et al., 2023). Although there are many studies on the effects of food processing on n-3 LC-PUFA in seafood, these information are less organized.

In this context, this study was conducted to provide a systematic and comprehensive review of the effects of food processing and storage on the lipid nutritional quality of fish and shellfish. The information in this article is very useful for understanding the current state of research and determining the direction of future research. In addition, this article also provides information to help consumers determine the best food processing and storage methods for maintaining lipid nutritional quality based on their preferences for specific lipid nutritional quality indicators.

2. Effects of food processing on the lipid content of fish and shellfish

In general, there is no general agreement on the effects of cooking on the lipid content of fish and shellfish. On the one hand, some studies have demonstrated that cooking caused reduction in lipid content of fish (e.g. Cyprian et al., 2015; Golgolipour et al., 2019; Sardenne et al., 2021) and shellfish (e.g. Purwaningsih et al., 2015; Biandolino et al., 2021). For example, microwave cooking of the Mediterranean mussel *Mytilus galloprovincialis* resulted in a 16 % reduction in lipid content (Biandolino et al., 2021); the steaming of the Atlantic markerel *Scomber scombrus* caused a 23 % reduction of lipid content (Sardenne et al., 2021); cooking (poaching, steaming and frying) of grass carp *Ctenopharyngodon idella* can reduce lipid content by 13 to 27 % (Golgolipour et al., 2019). The reduction in lipid content is attributed to thermal treatment induced oxidation of lipids during cooking, resulting in the formation of various lipid oxidation products, including malondialdehyde (MDA), α-dicarbonyl compounds, α,β-unsaturated aldehydes etc. (Zhuang et al., 2022).

On the other hand, many more studies have shown that cooking increases the total lipid content of cooked fish (e.g. Sardenne et al., 2021; Tenyang et al., 2022; Biandolino et al., 2023) and shellfish (e.g. Biandolino et al., 2021; Peycheva et al., 2022), in which authors explained these observations are attributed to the reduction in moisture of fish and shellfish during cooking (e.g. Tenyang et al., 2022; Biandolino et al., 2023). However, although cooking does reduce the moisture of fish and shellfish, the lipid content of cooked fish and shellfish on a dry weight basis (Table 1 and Table 2) also showed a clear increase, indicating that the increase of lipid content during cooking is independent of reduction in moisture. In fact, some of these studies have shown that the increase of lipid content is associated with the decrease of ash and protein content. For example, cooking (steaming, oven cooking and frying with olive oil) of Meagre *Argyrosomus regius* caused increase of lipid content (%DW) by 144 % to 332 %, but reduction in ash (%DW) and protein content (%DW) by up to 7 % and 15 %, respectively (Alexi et al., 2019). Similarly, in cupped oysters *Crassostrea gigas*, cooking increases lipid content by 27 % to 32 %, but reduces protein and ash content by 9 % and 7 %, respectively (Felici et al., 2019). It is worth noting that some studies revealed that cooking increases the content of lipids, proteins and ash (e.g. Garcia-Arias et al., 2003; Golgolipour et al., 2019; Tenyang et al., 2022). For example, Tenyang et al. (2022) reported that cooking (boiling, frying with palmor oil, smooking and steaming) of *Polypterus bichir bichir* resulted in an increase in Ash (% DW), lipids (%DW) and protein (%DW) by up to 16 %, 28 % and 6 %, respectively. Therefore, more studies are highly recommended to reveal the effects of food processing on changes in the nutritional composition of fish and shellfish.Table 3.Table 4..

Among cooking methods, frying causes the highest increment in lipid content of fish (e.g. Biandolino et al., 2021, 2023). For example, fried red mullet *Mullus barbatus* (Biandolino et al., 2023), Mediterranean mussels *Mytilus galloprovincialis* (Biandolino et al., 2021) and blue mussels *Mytilus edulis* (Czech et al., 2015) resulted in an increase of total lipid content by 11.5 fold, 2.4 fold and 45 fold, respectively. This is not surprising, as fish and shellfish can absorb oil from the cooking medium during the frying process. The changes in lipid content during frying is highly depend on the type of cooking oil used (Weber et al., 2008; Echarte et al., 2001; Zotos et al., 2013). For example, Zotos et al. (2013) have shown that the lipid content of Anchovy *Engraulis encrasicholus* fried in sunflower oil was 12.7 % to 16 % higher than that fried with olive oil. In fried salmon, Echarte et al. (2001) recorded a 5 % higher lipid content in salmon fried with olive oil than that fried with soya oil. However, contradictory results have been documented in some studies, in which no significant changes were observed in the lipid of silver catfish *Rhamdia quelen* fried with different cooking mediums (soybean oil, canola oil and hydrogenated vegetable oil) (Weber et al., 2008). In addition, the effects of frying medium on the lipid content of seafood is also highly influenced by the species. For example, Agren and Hanninen (1993) demonstrated that the lipid content of rainbow trout *Oncorhynchus mykiss* and Pike *Esox lucius* fried with rapeseed oil was significantly higher than that of rainbow fish fried with sunflower oil. However, there was no significant difference in lipid content of Vendace *Coregonus albula* fried with sunflower and rapeseed oils.

As for cold storage of fish and shellfish, most studies on cold storage did not provide information on total lipids, with the only available report for short-term refrigeration storage revealed that the total lipid content in Atlantic markerel *Scomber scombrus* fillets decreased significantly after 12 days of storage at 2–4 °C (Sardenne et al., 2021). However, contradictory results have been documented in the only available report for frozen storage, in which reported the total lipid content of Atlantic hake *Merluccius hubbsi* increased significantly when stored at −18 °C for 120 days (Saldanha and Bragagnolo, 2008). It is obvious that more studies is required in the future to draw solid conclusions.

3. Effects of food processing on the omega-3 LC-PUFA of fish and shellfish

As mentioned earlier, fish and shellfish are rich in n-3 LC-PUFA, with EPA and DHA being the dominant n-3 LC-PUFA (Tan et al., 2021a). Since many studies have confirmed the health benefits of EPA and DHA (e.g Calder, 2018; Li et al., 2021; Mohan et al., 2021), and these fatty acids cannot be adequately biosynthesized by humans, seafood is a vital source of the human dietary EPA and DHA. In fact, the current average intake of EPA and DHA in most of the world's population is far below the recommended levels. Therefore, food processing approach (cooking and storing) that cause minimum loss or highest preservation of EPA and DHA are preferable.

In general, all studies agreed that frying decreases the content of EPA and DHA in seafood, mainly through direct destruction caused by heat treatment (Gall et al., 1983; Agren and Hanninen, 1993; Castrillon et al., 1999; Candela et al., 1998; Garcia-Arias et al., 2003; Otles and Sengor, 2005; Sioen et al., 2006; Su and Babb, 2007; Weber et al., 2008; Türkkan et al., 2008; Marichamy et al., 2009; Larsen et al., 2010; Musaiger and D'Souza, 2011; Zotos et al., 2013; Zhang et al., 2013; Hosseini et al., 2014; Neff et al., 2014; Czech et al., 2015; Ghribi et al., 2017; Choo et al., 2018; Wright et al., 2018; Alexi et al., 2019; Bejaoui et al., 2019; Golgolipour et al., 2019; Alexi et al., 2019; Biandolino et al., 2023). This

Table 1
Effects of food processing on the lipid nutritional quality of fish.

Common name	Species	Cooking methods	Total lipid (% DW)	EPA + DHA (%)	n3/n6	PUFA/SFA	References
Red mullet	*Mullus barbatus*	Grilled, oven cooked, fried, microwaved, and boiled	Fresh = 2.00; grilled = 2.00; oven cooked = 2.00; fried (olive oil) = 23.00; microwaved = 3.50; boiled = 1.80	Fresh = 25.58; grilled = 25.81; oven cooked = 19.61; fried = 5.00; microwaved = 24.41; boiled = 25.02	Fresh = 4.47; grilled = 3.65; oven cooked = 3.08; fried = 1.25; microwaved = 3.59; boiled = 3.11	Fresh = 1.04; grilled = 1.00; oven cooked = 0.89; fried = 0.69; microwaved = 0.93; boiled = 1.02	Biandolino et al., 2023
Nile bichir	*Polypterus bichir bichir*	Boiled, fried (palmor oil), fried + boiled, smoked, smoked + boiled, steamed	Fresh = 21.50; boiled = 23.06; fried = 27.57; fried + boiled = 24.35; smoked = 25.41; smoked + boiled = 21.70; steamed = 25.76	–	–	–	Tenyang et al., 2022
Atlantic markerel	*Scomber scombrus*	Grilled and steamed	Fresh = 6.09; grilled = 6.65; steamed = 4.69	Fresh = 1.62; grilled = 1.65; steamed = 1.29	–	Fresh = 1.27; grilled = 1.21; steamed = 1.35	Sardenne et al., 2021
Smooth weakfish	*Cynoscion leiarchus*	Braised	Fresh = 6.85; braised = 16.70	Fresh = 13.41; braised = 4.10	Fresh = 3.43; braised = 0.56	Fresh = 0.53; braised = 1.25	Brito et al., 2019
Meagre	*Argyrosomus regius*	Steamed, oven cooked and fried (olive oil)	Fresh = 3.20; steamed = 8.28; oven cooked = 7.78; fried = 13.79	Fresh = 15.58; steamed = 14.64; oven cooked = 14.38; fried = 8.32	Fresh = 1.19; steamed = 1.20; oven cooked = 1.18; fried = 0.97	Fresh = 1.23; steamed = 1.23; oven cooked = 1.23; fried = 0.95	Alexi et al., 2019
Grass carp	*Ctenopharyngodon idella*	Poached, steamed, microwaved, pan fried (without oil) and deep fried (olive oil)	Fresh = 6.93; poached = 4.59; steamed = 5.81; microwaved = 6.46; pan fried = 4.81; deep fried = 19.38	Fresh = 0.77; poached = 0.67; steamed = 0.56; microwaved = 0.72; pan fried = 1.55; deep fried = 0.59	Fresh = 0.33; poached = 0.28; steamed = 0.27; microwaved = 0.26; pan fried = 0.30; deep fried = 0.35	Fresh = 0.41; poached = 0.43; steamed = 0.46; microwaved = 0.49; pan fried = 0.48; deep fried = 0.47	Golgolipour et al., 2019
Seabream	*Sparus aurata*	Steamed, oven cooked and fried (olive oil)	Fresh = 22.69; steamed = 24.69; oven cooked = 28.81; fried = 27.06	Fresh = 7.76; steamed = 7.54; oven cooked = 7.90; fried = 6.41	Fresh = 0.71; steamed = 0.69; oven cooked = 0.70; fried = 0.69	Fresh = 0.97; steamed = 0.97; oven cooked = 0.99; fried = 0.90	Alexi et al., 2019
Salmon	*Salmo salar*	Steamed, fried (palm oil), grilled and baked	–	Fresh = 2.55; steamed = 3.59; fried = 1.89; grilled = 2.89; baked = 3.51	–	Fresh = 1.01; steamed = 1.17; fried = 0.56; grilled = 1.11; baked = 1.20	Choo et al., 2018
Japanese threadfin bream	*Nemipterus japonicus*	Steamed, fried (palm oil), grilled and baked	–	Fresh = 1.87; steamed = 2.90; fried = 1.26; grilled = 2.21; baked = 3.04	–	Fresh = 0.13; steamed = 0.17; fried = 0.08; grilled = 0.13; baked = 0.17	Choo et al., 2018
Yellowstripe scad	*Selaroides leptolepis*	Steamed, fried (palm oil), grilled and baked	–	Fresh = 8.06; steamed = 12.31; fried = 8.43; grilled = 11.75; baked = 12.77	–	Fresh = 0.35; steamed = 0.54; fried = 0.32; grilled = 0.48; baked = 0.52	Choo et al., 2018
Common carp	*Cyprinus carpio*	Smoked	Fresh = 3.41; smoked = 5.00	Fresh = 2.43; smoked = 2.58	Fresh = 0.26; smoked = 0.25	Fresh = 1.12; smoked = 1.14	Ljubojevic et al., 2016
Sardine	*Sardinella gibbosa*	Hot-smoked and cold-smoked	Fresh = 6.7; hot-smoked = 4.8; cold-smoked = 5.6	Fresh = 20.53; hot-smoked = 21.08; cold-smoked = 20.85	–	Fresh = 0.65; hot-smoked = 0.71; cold-smoked = 0.71	Cyprian et al., 2015
Capelin	*Mallotus villosus*	Hot-smoked and cold-smoked	Fresh = 10.2; hot-smoked = 7.4; cold-smoked = 8.2	Fresh = 12.77; hot-smoked = 17.96; cold-smoked = 17.72	–	Fresh = 0.98; hot-smoked = 1.19; cold-smoked = 1.23	Cyprian et al., 2015
Lake trout	*Salvelinus namaycush*	Baked, broiled and fried	–	Fresh = 15.54; baked = 13.66; broiled = 15.01; fried = 12.97	Fresh = 2.70; baked = 2.30; broiled = 2.60; fried = 2.10	Fresh = 1.60; baked = 1.60; broiled = 1.60; fried = 1.70	Neff et al., 2014
White sucker	*Catostomus commersonii*	Baked, broiled and fried	–	Fresh = 24.31; baked = 10.95; broiled = 16.17; fried = 5.58	Fresh = 3.90; baked = 1.70; broiled = 2.30; fried = 0.90	Fresh = 1.30; baked = 1.80; broiled = 1.40; fried = 2.50	Neff et al., 2014
Kutum roach	*Rutilus frisii kutum*	Baked, boiled, microwaved and fried	Fresh = 15.49; baked = 16.95; boiled = 13.31; microwaved = 16.40; fried = 21.10	Fresh = 2.50; baked = 1.67; boiled = 1.31; microwaved = 0.96; fried = 1.19	Fresh = 3.89; baked = 1.89; boiled = 3.61; microwaved = 2.03; fried = 0.43	Fresh = 1.08; baked = 1.06; boiled = 1.03; microwaved = 1.02; fried = 1.79	Hosseini et al., 2014
Common carp	*Cyprinus carpio carpio*	Baked, broiled and fried	–	Fresh = 2.19; baked = 1.39; broiled = 1.07; fried = 1.62	Fresh = 0.50; baked = 0.40;	Fresh = 0.60; baked = 0.60; broiled = 0.40; fried = 0.80	Neff et al., 2014

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Table 1 (*continued*)

Common name	Species	Cooking methods	Total lipid (% DW)	EPA + DHA (%)	n3/n6	PUFA/SFA	References
					broiled = 0.30; fried = 0.40		
Chinook salmon	*Oncorhynchus tshawytscha*	Baked, broiled and fried	–	Fresh = 20.78; baked = 16.35; broiled = 18.55; fried = 11.29	Fresh = 2.92; baked = 2.19; broiled = 2.52; fried = 1.54	Fresh = 2.20; baked = 2.10; broiled = 2.10; fried = 2.30	Neff et al., 2014
walleye	*Sander vitreus*	Baked, broiled and fried	–	Fresh = 22.41; baked = 16.65; broiled = 12.87; fried = 7.33	Fresh = 3.00; baked = 2.10; broiled = 1.80; fried = 1.00	Fresh = 1.70; baked = 1.80; broiled = 1.90; fried = 2.40	Neff et al., 2014
Anchovy	*Engraulis encrasicholus*	Fried (sunflower oil) for 2 to 5 min	Fresh = 7.04; fried 2 min = 39.34; fried 3 min = 42.61; fried 4 min = 52.00; fried 5 min = 53.14	Fresh = NIL; fried 2 min = 0.21; fried 3 min = 0.25; fried 4 min = 0.24; fried 5 min = 0.24	Fresh = 0.13; fried 2 min = 35.25; fried 3 min = 22.00; fried 4 min = 26.4; fried 5 min = 27.00	Fresh = 0.53; fried 2 min = 0.11; fried 3 min = 0.11; fried 4 min = 0.11; fried 5 min = 0.11	Zotos et al., 2013
Sardine	*Sardina pilchardus*	Baked for 20–60 min	Fresh = 13.23; baked 20 min = 11.86; baked 40 min = 11.91; baked 50 min = 12.04; baked 60 min = 12.05	Fresh = 33.03; baked 20 min = 33.16; baked 40 min = 33.16; baked 50 min = 33.43; baked 60 min = 34.18	Fresh = 9.30; baked 20 min = 9.40; baked 40 min = 9.40; baked 50 min = 9.50; baked 60 min = 9.90	Fresh = 1.06; baked 20 min = 1.02; baked 40 min = 1.03; baked 50 min = 1.03; baked 60 min = 1.06	Zotos et al., 2013
Grass carp	*Ctenopharynyodon idellus*	Boiled, steamed, microwaved, grilled, pan-fried (soybean oil) and deep-fried (soybean oil)	Fresh = 8.74; boiled = 7.46; steamed = 7.33; microwaved = 9.14; grilled = 9.65; pan-fried = 24.72; deep-fried = 25.15	Fresh = 10.73; boiled = 11.27; steamed = 10.34; microwaved = 9.95; grilled = 9.14; pan-fried = 4.34; deep-fried = 4.00	Fresh = 0.95; boiled = 0.91; steamed = 0.91; microwaved = 0.97; grilled = 0.98; pan-fried = 0.26; deep-fried = 0.25	Fresh = 2.61; boiled = 2.34; steamed = 2.52; microwaved = 2.22; grilled = 2.31; pan-fried = 3.62; deep-fried = 4.23	Zhang et al., 2013
Anchovy	*Engraulis encrasicholus*	Fried (olive oil) for 2 to 5 min	Fresh = 10.08; fried 2 min = 33.81; fried 3 min = 37.50; fried 4 min = 40.91; fried 5 min = 41.04	Fresh = 33.36; fried 2 min = 3.95; fried 3 min = 3.11; fried 4 min = 2.96; fried 5 min = 2.76	Fresh = 15.62; fried 2 min = 2.56; fried 3 min = 0.73; fried 4 min = 0.71; fried 5 min = 0.73	Fresh = 0.99; fried 2 min = 0.20; fried 3 min = 0.24; fried 4 min = 0.24; fried 5 min = 0.35	Zotos et al., 2013
Red mullet	*Mullus barbatus*	Oven-cooked, steamed, fried (corn oil) and microwaved	Fresh = 13.37; oven-cooked = 14.00; steamed = 13.00; fried = 34.44; microwaved = 11.00	Fresh = 1.11; oven-cooked = 0.93; steamed = 0.76; fried = 0.80; microwaved = 0.99	Fresh = 1.31; oven-cooked = 1.33; steamed = 0.03; fried = 0.64; microwaved = 1.30	Fresh = 0.08; oven-cooked = 0.06; steamed = 2.19; fried = 0.06; microwaved = 0.06	Koubaa et al., 2012
Pear spotted rabbitfish	*Siganus canaliculatus*	Curried and fried (corn oil)	–	Fresh = 7.96; curried = 3.03; fried = 2.91	–	Fresh = 0.50; curried = 2.23; fried = 2.12	Musaiger and D'Souza, 2011
Striped catfish	*Pangasius hypophthalmus*	Boiled, boiled with salt, microwaved with water, microwaved and fried (rapeseed oil)	Fresh = 12.14; boiled = 10.44; boiled with salt = 10.24; microwaved with water = 14.58; microwaved = 15.23; fried = 26.28	Fresh = 1.04; boiled = 1.09; boiled with salt = 0.98; microwaved with water = 1.20; microwaved = 0.95; fried = 0.29	Fresh = 0.41; boiled = 0.43; boiled with salt = 0.39; microwaved with water = 0.41; microwaved = 0.34; fried = 0.46	Fresh = 0.26; boiled = 0.47; boiled with salt = 0.26; microwaved with water = 0.25; microwaved = 0.25; fried = 1.86	Domiszewski et al., 2011
Diamon mullet	*Liza alata*	Grilled	–	Fresh = 7.69; grilled = 9.17	–	Fresh = 0.35; grilled = 0.47	Musaiger and D'Souza, 2011
Narrow-barred Spanish mackrel	*Scomberomorus commerson*	Curried	–	Fresh = 21.33; curried = 18.96	–	Fresh = 0.78; curried = 1.13	Musaiger and D'Souza, 2011
Grey grunt	*Plectorhinchus sordidus*	Grilled	–	Fresh = 10.81; grilled = 12.69	–	Fresh = 0.69; grilled = 0.80	Musaiger and D'Souza, 2011
New Zealand King Salmon	*Oncorhynchus tshawytscha*	Poached, steamed, microwaved, oven baked, pan fried and deep fried	Fresh = 21.61; poached = 18.02; steamed = 21.20; microwaved = 18.32; oven baked = 24.68; pan fried = 23.14; deep fried = 26.30	Fresh = 13.06; poached = 6.03; steamed = 12.71; microwaved = 12.79; oven baked = 12.22; pan fried = 11.83; deep fried = 4.47	Fresh = 1.48; poached = 1.45; steamed = 1.42; microwaved = 1.39; oven baked = 1.37; pan fried = 1.33; deep fried = 0.56	Fresh = 1.01; poached = 1.03; steamed = 1.04; microwaved = 1.04; oven baked = 0.99; pan fried = 0.97; deep fried = 1.43	Larsen et al., 2010

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Table 1 (*continued*)

Common name	Species	Cooking methods	Total lipid (% DW)	EPA + DHA (%)	n3/n6	PUFA/SFA	References
Indian mackerel	*Bastrilliger kanagurta*	Fried and gravy	–	Fresh = 6.42; fried = 2.99; gravy = 11.49	Fresh = 0.40; fried = 0.19; gravy = 1.01	Fresh = 0.91; fried = 0.82; gravy = 1.09	Marichamy et al., 2009
Seabass	*Dicentrarchus labrax*	Fried (sunflower oil), baked and microwaved	Fresh = 14.73; fried = 18.63; baked = 17.54; microwaved = 16.77	Fresh = 20.69; fried = 14.84; baked = 20.22; microwaved = 23.22	Fresh = 2.02; fried = 0.55; baked = 1.51; microwaved = 2.24	Fresh = 0.96; fried = 1.62; baked = 1.08; microwaved = 1.11	Türkkan et al., 2008
Atlantic hake	*Merluccius hubbsi*	Grilled	Fresh = 8.6; grilled = 7.9	Fresh = 21.89; grilled = 25.52	Fresh = 5.27; grilled = 5.19	Fresh = 1.07; grilled = 1.35	Saldanha and Bragagnolo, 2008
Silver catfish	*Rhamdia quelen*	Boiled, baked, microwaved, grilled, fried (soybean oil), fried (canola oil) and fried (hydrogenated vegetable oil)	Fresh = 15.50; boiled = 20.10; baked = 23.00; microwaved = 21.90; grilled = 25.70; fried (soybean oil) = 33.40; fried (canola oil) = 32.05; fried (hydrogenated vegetable oil) = 32.20	Fresh = 3.90; boiled = 4.89; baked = 3.81; microwaved = 3.76; grilled = 4.07; fried (soybean oil) = 0.73; fried (canola oil) = 1.27; fried (hydrogenated vegetable oil) = 1.37	Fresh = 0.29; boiled = 0.35; baked = 0.29; microwaved = 0.30; grilled = 0.28; fried (soybean oil) = 0.12; fried (canola oil) = 7.81; fried (hydrogenated vegetable oil) = 0.13	Fresh = 1.81; boiled = 1.77; baked = 1.86; microwaved = 1.81; grilled = 1.95; fried (soybean oil) = 4.55; fried (canola oil) = 5.39; fried (hydrogenated vegetable oil) = 1.42	Weber et al., 2008
Indo-Pacific king mackerel	*Scomberomorous guttatus*	Microwaved, grilled, steamed and shallow fat fried (palm oil)	Fresh = 6.00; microwaved = 7.00; grilled = 10.48; steamed = 5.42; shallow fat fried = 10.30	Fresh = 18.72; microwaved = 18.51; grilled = 18.29; steamed = 18.30; shallow fat fried = 12.79	Fresh = 1.85; microwaved = 1.92; grilled = 1.82; steamed = 1.75; shallow fat fried = 0.78	Fresh = 0.89; microwaved = 0.85; grilled = 0.84; steamed = 0.87; shallow fat fried = 0.95	Bakar et al., 2008
Nile tilapia	*Oreochromis niloticus*	Roasted and steamed	–	Fresh = 3.10; roasted = 3.40; steamed = 3.70	Fresh = 0.73; roasted = 0.71; steamed = 0.80	Fresh = 0.35; roasted = 0.36; steamed = 0.37	de Castro et al., 2007
Siberian trout	*Salmo trutta*	Boiled and fried (Sunflower oil)	–	Fresh = 30.98; boiled = 48.44; fried = 35.18	Fresh = 7.82; boiled = 5.88; fried = 4.86	Fresh = 1.57; boiled = 1.62; fried = 2.00	Gladyshev et al., 2007
Rainbow trout	*Oncorhynchus mykiss*	Oven cooked and microwaved	Fresh = 8.02; oven cooked = 14.82; microwaved = 19.16	Fresh = 11.32; oven cooked = 11.59; microwaved = 11.90	Fresh = 1.94; oven cooked = 1.77; microwaved = 1.86	Fresh = 0.68; oven cooked = 0.72; microwaved = 0.76	Unusan, 2007
Common carp	*Cyprinus carpio*	Roasted and steamed	–	Fresh = 1.5; roasted = 0.6; steamed = 1.5	Fresh = 0.18; roasted = 0.10; steamed = 0.17	Fresh = 0.60; roasted = 0.50; steamed = 0.60	de Castro et al., 2007
Norwegian trout	*Salmo trutta*	Boiled and fried (Sunflower oil)	–	Fresh = 22.94; boiled = 26.23; fried = 26.82	Fresh = 4.81; boiled = 4.26; fried = 5.24	Fresh = 1.35; boiled = 1.45; fried = 1.73	Gladyshev et al., 2007
Herring	*Clupea harengus pallasi*	Boiled and fried (Sunflower oil)	–	Fresh = 30.00; boiled = 23.98; fried = 30.99	Fresh = 19.70; boiled = 21.10; fried = 9.39	Fresh = 1.01; boiled = 0.67; fried = 1.09	Gladyshev et al., 2007
Tambacu	*Colossoma macropomum* x *Piaractus mesopotamicus*	Roasted and steamed	–	Fresh = 3.00; roasted = 3.20; steamed = 2.90	Fresh = 0.59; roasted = 0.60; steamed = 0.74	Fresh = 0.40; roasted = 0.40; steamed = 0.40	de Castro et al., 2007
Sole	*Lepidopsetta bilineata*	Boiled and fried (Sunflower oil)	–	Fresh = 33.09; boiled = 33.40; fried = 31.88	Fresh = 9.97; boiled = 7.92; fried = 1.87	Fresh = 1.05; boiled = 0.81; fried = 1.06	Gladyshev et al., 2007
Cod	*Gadus morhua marisalbi*	Boiled and fried (Sunflower oil)	–	Fresh = 51.69; boiled = 53.16	Fresh = 43.70; boiled = 41.30	Fresh = 1.42; boiled = 1.74	Gladyshev et al., 2007
humpback salmon	*Oncorhynchus gorbuscha*	Boiled, fried (sunflower oil), and roasted	–	Fresh = 26.45; boiled = 28.40; fried = 20.58; roasted = 19.64	Fresh = 16.2; boiled = 15.9; fried = 2.20; roasted = 3.40	–	Gladyshev et al., 2006
Salmon	*Salmo salar*	Fried (margarine), fried (olive oil)	–	Fresh = 19.17; fried (margarine) = 17.96; fried (olive oil) = 15.21	Fresh = 3.33; fried (margarine) = 3.13; fried (olive oil) = 3.13	Fresh = 1.30; fried (margarine) = 1.03; fried (olive oil) = 1.14	Sioen et al., 2006
Cod	*Gadus morhua*	Fried (margarine), fried (olive oil)	–	Fresh = 49.61; fried (margarine) = 9.83; fried (olive oil) = 12.27	Fresh = 10.00; fried (margarine) = 1.37; fried (olive oil) = 2.50	Fresh = 2.16; fried (margarine) = 0.33; fried (olive oil) = 1.16	Sioen et al., 2006
Sardine	*Sardina pilchardus*	Fried (olive oil), baked and grilled	Fresh = 39.25; fried = 37.33; baked = 32.99; grilled = 33.35	Fresh = 29.45; fried = 12.71; baked = 30.22; grilled = 29.76	Fresh = 26.76; fried = 3.83; baked = 26.35; grilled = 27.73	Fresh = 1.16; fried = 0.95; baked = 1.14; grilled = 1.25	Garcia-Arias et al., 2003

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Table 1 (*continued*)

Common name	Species	Cooking methods	Total lipid (% DW)	EPA + DHA (%)	n3/n6	PUFA/SFA	References
Herring		Boiled (microwave), boiled (conventionally), grilled (microwave), grilled (conventioanally), fried (microwave + “Smazyk” cooking oil) and fried (conventionally + “Smazyk” cooking oil)	–	Fresh = 13.80; boiled (microwave) = 15.00; boiled (conventionally) = 12.90; grilled (microwave) = 12.70; grilled (conventioanally) = 14.50; fried (microwave + “Smazyk” cooking oil) = 13.60; fried (conventionally + “Smazyk” cooking oil) = 13.70	–	Fresh = 0.93; boiled (microwave) = 0.94; boiled (conventionally) = 0.91; grilled (microwave) = 0.91; grilled (conventioanally) = 1.01; fried (microwave + “Smazyk” cooking oil) = 0.85; fried (conventionally + “Smazyk” cooking oil) = 1.16	Regulska-Ilow and Ilow, 2002
Salmon		Fried (olive oil), fried (soya oil) and roasted	Fresh = 9.76; fried (olive oil) = 19.54; fried (soya oil) = 17.97; roasted = 8.57	Fresh = 17.51; fried (olive oil) = 16.73; fried (soya oil) = 15.94; roasted = 15.85	Fresh = 6.48; fried (olive oil) = 4.27; fried (soya oil) = 3.23; roasted = 3.34	Fresh = 1.29; fried (olive oil) = 1.21; fried (soya oil) = 1.39; roasted = 1.57	Echarte et al., 2001
sardine	*Sardine pilchardus*	Fried (sunflower oil) and warmheld	–	Fresh = 31.81; fried = 7.88; warmheld = 7.80	Fresh = 14.29; fried = 0.17; warmheld = 0.17	Fresh = 1.04; fried = 3.62; warmheld = 3.58	Candela et al., 1998
Spanish mackerel	*Scomberomorus commersoni*	Fried (sunflower oil) and warmheld	–	Fresh = 24.98; fried = 6.91; warmheld = 5.43	Fresh = 8.33; fried = 0.16; warmheld = 0.13	Fresh = 0.98; fried = 3.55; warmheld = 3.49	Candela et al., 1998
	Salmon salar	Fried (sunflower oil) and warmheld	–	Fresh = 18.83; fried = 15.24; warmheld = 17.74	Fresh = 8.33; fried = 0.93; warmheld = 1.61	Fresh = 0.78; fried = 1.45; warmheld = 1.24	Candela et al., 1998
sardine	*Sardine pilchardus*	Fried (olive oil)	Fresh = 3.93; fried = 3.73	Fresh = 29.36; fried = 12.77	Fresh = 4.05; fried = 2.08	Fresh = 1.34; fried = 1.09	Castrillion et al., 1999
Vendace	*Coregonus albula*	Boiled, baked, microwaved, fried (sunflower oil) and fried (rapeseed oil)	Fresh = 3.52; boiled = 5.17; baked = 4.85; microwaved = 6.04; fried (sunflower oil) = 23.94; fried (rapeseed oil) = 23.46	Fresh = 38.81; boiled = 25.74; baked = 32.12; microwaved = 30.14; fried (sunflower oil) = 5.38; fried (rapeseed oil) = 6.41	Fresh = 3.83; boiled = 3.53; baked = 3.51; microwaved = 3.38; fried (sunflower oil) = 0.15; fried (rapeseed oil) = 0.70	Fresh = 2.39; boiled = 2.25; baked = 1.26; microwaved = 2.24; fried (sunflower oil) = 4.69; fried (rapeseed oil) = 3.95	Agren and Hamminen, 1993
Rainbow trout	*Oncorhynchus mykiss*	Boiled, baked, microwaved, fried (sunflower oil) and fried (rapeseed oil)	Fresh = 10.55; boiled = 15.05; baked = 12.69; microwaved = 15.09; fried (sunflower oil) = 14.61; fried (rapeseed oil) = 19.63	Fresh = 28.81; boiled = 23.79; baked = 25.24; microwaved = 24.05; fried (sunflower oil) = 18.48; fried (rapeseed oil) = 20.76	Fresh = 6.45; boiled = 4.98; baked = 5.18; microwaved = 5.03; fried (sunflower oil) = 1.14; fried (rapeseed oil) = 3.63	Fresh = 2.05; boiled = 1.78; baked = 1.70; microwaved = 36.89; fried (sunflower oil) = 2.52; fried (rapeseed oil) = 1.62	Agren and Hamminen, 1993
Pike	*Esox lucius*	Boiled, baked, microwaved, fried (sunflower oil) and fried (rapeseed oil)	Fresh = 1.93; boiled = 2.19; baked = 1.56; microwaved = 1.43; fried (sunflower oil) = 7.43; fried (rapeseed oil) = 9.89	Fresh = 57.21; boiled = 55.13; baked = 51.74; microwaved = 57.21; fried (sunflower oil) = 15.52; fried (rapeseed oil) = 6.07	Fresh = 11.18; boiled = 10.38; baked = 7.80; microwaved = 8.74; fried (sunflower oil) = 0.34; fried (rapeseed oil) = 0.69	Fresh = 2.73; boiled = 2.62; baked = 0.72; microwaved = 2.99; fried (sunflower oil) = 4.25; fried (rapeseed oil) = 3.69	Agren and Hamminen, 1993
red snapper	*Lutjanus campechanus*	Baked, broiled, deep fried (soybean oil) and microwaved	Fresh = 1.50; baked = 1.31; broiled = 1.75; deep fried = 5.49; microwaved = 1.65	Fresh = 26.41; baked = 28.33; broiled = 27.01; deep fried = 7.53; microwaved = 29.79	–	Fresh = 1.27; baked = 1.39; broiled = 1.42; deep fried = 2.60; microwaved = 1.34	Gall et al., 1983
grouper	*Epinephelus morio*	Baked, broiled, deep fried (soybean oil) and microwaved	Fresh = 0.88; baked = 1.14; broiled = 1.18; deep fried = 3.73; microwaved = 1.41	Fresh = 27.06; baked = 28.00; broiled = 26.34; deep fried = 6.06; microwaved = 16.71	–	Fresh = 1.35; baked = 1.30; broiled = 1.43; deep fried = 2.36; microwaved = 1.06	Gall et al., 1983
Spanish mackerel	*Scomberomorus macuhtus*	Baked, broiled, deep fried (soybean oil) and microwaved	Fresh = 13.75; baked = 12.65; broiled = 13.18; deep fried = 12.42;	Fresh = 21.14; baked = 19.31; broiled = 21.42; deep fried = 19.34; microwaved = 19.63	–	Fresh = 0.99; baked = 0.83; broiled = 0.88; deep fried = 1.29; microwaved = 0.85	Gall et al., 1983

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Table 1 (*continued*)

Common name	Species	Cooking methods	Total lipid (% DW)	EPA + DHA (%)	n3/n6	PUFA/SFA	References
			microwaved = 13.61				
Florida pompano	*Trachinotus carolinus*	Baked, broiled, deep fried (soybean oil) and microwaved	Fresh = 5.17; baked = 4.48; broiled = 4.19; deep fried = 8.78; microwaved = 4.21	Fresh = 9.32; baked = 9.32; broiled = 11.14; deep fried = 4.81; microwaved = 9.61	–	Fresh = 0.56; baked = 0.56; broiled = 0.61; deep fried = 1.47; microwaved = 0.61	Gall et al., 1983

DW = dried weight.

is due to the fact that EPA and DHA are highly unsaturated, and thus highly susceptible to oxidation (Weber et al., 2008; Zhou et al., 2019).

On the other hand, the reduction in the relative composition of EPA + DHA in fried seafood is attributed to the exchange of fatty acids between cooking oil (poor in n-3 LC-PUFA) and seafood (Agren and Hanninen, 1993; Echarte et al., 2001; Weber et al., 2008; Zotos et al., 2013; Bejaoui et al., 2019). For example, in a study comparing the fatty acid profiles of carpet shell *Veneruois decussate* and margarine, before and after frying, Bejaoui et al. (2019) demonstrated that frying reduced the EPA + DHA content in clam by 77 %, while increased the n-3 LC-PUFA content in margarine by 62.6 %. In a study of frying anchovy *Engraulis encrasicholus* with olive oil and sunflower oil, Zotos et al. (2013) revealed that the EPA + DHA content in anchovy decreased from 33.36 to 45.12 % to 1.34–3.95 %, while the EPA + DHA content in cooking oils increased from undetectable to 0.21–0.34 %.

In addition to frying, some studies revealed that oven cooking (Alexi et al., 2019; Biandolino et al., 2023), roasting (de Castro et al., 2007), microwave cooking (Gall et al., 1983; Hosseini et al., 2014), baking (Hosseini et al., 2014; Neff et al., 2014), boiling (Agren and Hanninen, 1993; Gladyshev et al., 2007; Hosseini et al., 2014) and steaming (Golgolipour et al., 2019; Alexi et al., 2019) also compromise the n-3 LC-PUFA content in fish. The negative impact of food processing on EPA + DHA of seafood is highly depends on the cooking methods, with frying having the greatest negative impact on EPA + DHA (e.g. Golgolipour et al., 2019; Alexi et al., 2019; Biandolino et al., 2023), followed by oven cooking and microwave cooking, and then boiling, steaming and baking (Hosseini et al., 2014; Alexi et al., 2019).

In shellfish, in addition to frying, oven cooking (Biandolino et al., 2021), microwave cooking (Ozturan et al., 2022), boiling (Purwaningsih et al., 2015; Merdzhanova et al., 2018; Ozturan et al., 2022), steaming (Otles and Sengor, 2005; Purwaningsih et al., 2015; Wright et al., 2018; Peycheva et al., 2022) and smooking (Otles and Sengor, 2005) have also been shown to significantly reduce EPA + DHA content. The negative effects of culinary preparation methods on the EPA + DHA content of shellfish shows an overall decreasing order of frying > oven cooking > boiling > microwave cooking and steaming > smoking (e.g. Otles and Sengor, 2005; Purwaningsih et al., 2015; Bejaoui et al., 2019; Biandolino et al., 2021).

For short-term refrigeration storage, at 4 °C, the EPA + DHA content in Atlantic salmon *Salmo salar* fillets significantly decreased on day 7, but remain at the level until 28 days and onward (Bienkiewicz et al., 2022). Similarly, in whelk *Neverita didyma* (without shell) (Yu et al., 2020) and sardine *Sardinella gibbosa* (Chaijan et al., 2006), EPA + DHA content significantly decreased after 6 days of 4 °C storage. However, the lifespan of blue mussel *Mytilus edulis* (without shell) (Zhou et al., 2019) and catfish *Arius maculates* (whole fish) (Tenyang et al., 2017) in refrigeration is relatively short, with a significantly decrease in EPA + DHA content after 4 and 3 days of 4 °C storage, respectively. At 2 to 4 °C, Sardenne et al. (2021) revealed that the EPA + DHA content of Atlantic markerel *Scomber scombrus* fillets significantly decreased only after 12 days of storage. At 1 °C, Pirini et al. (2000) demonstrated that the EPA + DHA content of sea bass *Dicentrarchus labrax* fillets remain unchanged for 12 days of storage. In short, the optimum storage period for EPA and DHA at 4 °C is 3 days, and the optimum storage period can be extended to 12 days if store at < 4 °C.

For longer-term frozen storage, the optimum storage period largely depend on the tissue conditions of the seafood. For example, in a 45 days frozen storage experiment at −20 °C, the EPA + DHA content in tambacu *Colossoma macropomum* x *Piaractus mesopotamicus* skinless fillets significantly decreased, but increased in fillets with skin of the same fish species (de Castro et al., 2007). In herring *Clupea harengus*, frozen storage at −25 °C did not cause significant changes in EPA + DHA content in light muscles for 5 months, but in dark muscles, in the EPA + DHA content decreased significantly after 2 months (Dang et al., 2018). In addition, the optimal storage period varies greatly at different temperatures, and is negatively correlated with storage temperature. For example, in red tilapia *Oreochromis niloticus* × *Tilapia mosambicus* fillets, significant reduction in EPA + DHA content was recorded after 2 days and 18 months when store at −18 °C (Karami et al., 2013) and −20 °C (Karlsdottir et al., 2014), respectively. At −30 °C, no changes in EPA + DHA was documented even after 18 months (Karlsdottir et al., 2014).

4. Effects of food processing on the n3/n6 of fish and shellfish

It is generally believed that n-6 LC-PUFAs, especially arachidonic acid (ARA), is a pro-inflammatory fatty acid that can produce pro-inflammatory lipid mediators such as lipoxins, leukotrienes, thromboxanes and prostaglandins, which may have adverse effects to health (Calder, 2020). Therefore, a lower proportion of n-6 LC-PUFA, as reflected by a high n3/n6 ratio is generally considered beneficial for human health, especially in reducing the risk of cancer, high plasma lipids, coronary heart disease etc (Chen et al., 2019; Li et al., 2021; Mohan et al., 2021). For example, Chen et al. (2019) explored the effects of dietary n3/n6 ratio on the risk of hypertension in adult Americans over an 8 years period (2007–2014). The results revealed a strong negative relationship between n3/n6 ratio and hypertension.

The effects of cooking on the n3/n6 ratio of seafood is very similar to the effects of cooking on EPA + DHA, with frying having the greatest negative effects on the n3/n6 ratio of seafood. This is due to the fact that EPA and DHA are the main n-3 LC-PUFA in fish and shellfish (Tan et al., 2021a,b, 2022), and therefore the thermal oxidation of EPA and DHA indirectly reduced the n3/n6 ratio of seafood. In addition to thermal oxidation, the absorption of cooking oil by fish and shellfish during frying also contributed significantly in the reduction in n3/n6 ratio and the the type of cooking oil used in frying had a significant impact on the degree of n3/n6 ratio reduction (Agren and Hanninen, 1993; Echarte et al., 2001; Sioen et al., 2006; Weber et al., 2008; Bejaoui et al., 2019). For example, Bejaoui et al. (2019) compared the effects of frying medium on the n3/n6 ratio of fried carpet shell *Venerupis decussate*. The results revealed that the degree of decrease in the n3/n6 ratio in fried bivalves largely depends on the frying medium, in a decreasing order of margarine (-89 %) > corn oil (-41 %) > olive oil (-31 %). In fried silver catfish *Rhamdia quelen*, frying with soybean oil resulted in a slightly higher decrease in n3/n6 ratio (-59 %) compared to hydrogenated vegetable oil (-55 %) (Weber et al., 2008). Similarly, in fried Cod fish *Gadus morhua*, frying with margarine can cause greater reduction in n3/

Table 2
Effects of culinary treatments on the lipid nutritional quality of shellfish.

Common name	Species	Cooking methods	Total lipid (% DW)	EPA + DHA (%)	n3/n6	PUFA/SFA	References
Mediterranean mussel	*Mytilus galloprovincialis*	Steamed	Fresh = 8.08; steamed = 8.28	Fresh = 52.46; steamed = 49.75	Fresh = 7.69; steamed = 10	Fresh = 2.63; steamed = 1.91	Peycheva et al., 2022
Mediterranean mussel	*Mytilus galloprovincialis*	Grilled, boiled, microwaved, oven cooked and fried (sunflower oil)	Fresh = 9.50; grilled = 10.00; boiled = 9.50; microwaved = 8.00; oven cooked = 10.00; fried = 23.00	Fresh = 24.06 ± 1.34; grilled = 20.51 ± 0.92; boiled = 21.20 ± 0.92; microwaved = 20.11 ± 0.87; oven cooked = 18.32 ± 0.56; fried = 4.60 ± 0.63	Row = 6.01; grilled = 3.23; boiled = 3.84; microwaved = 3.64; oven cooked = 3.43; fried = 0.15	Fresh = 0.92; grilled = 1.14; boiled = 1.02; microwaved = 0.97; oven cooked = 1.00; fried = 35.37	Biandolino et al., 2021
Mediterranean mussel	*Mytilus galloprovincialis*	Steamed	–	Fresh = 19.69; steamed = 17.46	–	Fresh = 1.42; steamed = 1.42	Wright et al., 2018
Blue mussel	*Mytilus edulis*	Fried (sunflower oil)	Fresh = 0.72; fried = 32.42	Fresh = 27.27; fried = 2.96	Fresh = 3.52; fried = 0.07	Fresh = 0.94; fried = 5.42	Czech et al., 2015
Mediterranean mussel	*Mytilus galloprovincialis*	Fresh, steamed, fried (sunflower oil), pickled and smoked	–	Fresh = 26.40; steamed = 13.20; fried = 1.50; pickled = 21.8; smoked = 16.7	–	Fresh = 1.36; steamed = 3.23; fried = 2.20; pickled = 0.96; smoked = 1.27	Otles and Sengor, 2005
Pacific oyster	*Crassostrea gigas*	Fried (olive oil), gratin	Fresh = 13.7; fried = 14.19; gratin = 14.8	Fresh = 38.92; fried = 32.54; gratin = 32.49	Fresh = 5.33; fried = 3.58; gratin = 3.29	Fresh = 1.83; fried = 1.84; gratin = 1.75	Felici et al., 2019
Pacific oyster	*Crassostrea gigas*	Steamed	–	Fresh = 29.48; steamed = 29.91	–	Fresh = 1.75; steamed = 1.75	Wright et al., 2018
Estern oyster	*Crassostrea virginica*	Steamed and oven dried	–	Fresh = 18.30; steamed = 18.25; oven dried = 18.26	–	Fresh = 1.13; steamed = 1.12; oven dried = 1.12	Wright et al., 2018
Carpet shell	*Venerupis decussata*	Fried (corn oil), fried (olive oil) and fried (margarine)	–	Fresh = 17.41; fried (corn oil) = 10.27; fried (olive oil) = 12.02; fried (margarine) = 4.06	Fresh = 5.30; fried (corn oil) = 1.29; fried (olive oil) = 1.62; fried (margarine) = 0.56	Fresh = 0.85; fried (corn oil) = 0.77; fried (olive oil) = 0.88; fried (margarine) = 0.55	Bejaoui et al., 2019
Clam	mix	Steamed and fried	–	Fresh = 11.35; steamed = 14.56; fried = 1.21	–	Fresh = 1.00; steamed = 2.89; fried = 1.07	Wright et al., 2018
Noah's ark shell	*Arca noae*	Steamed, boiled, grilled and fried (olive oil)	–	Fresh = 8.02; steamed = 8.03; boiled = 9.03; grilled = 7.33; fried = 3.05	Fresh = 2.66; steamed = 1.46; boiled = 1.85; grilled = 1.38; fried = 0.27	Fresh = 1.03; steamed = 1.29; boiled = 0.90; grilled = 1.07; fried = 0.75	Ghribi et al., 2017
Asian clam	*Corbicula javanica*	Boiled, steamed and boiled with salt	Fresh = 4.99; boiled = 2.83; steamed = 3.09 and boiled with salt = 1.98	Fresh = 3.82; boiled = 2.39; steamed = 2.91; boiled with salt = 2.19	Fresh = 1.48; boiled = 2.14; steamed = 1.71; boiled with salt = 1.85	Fresh = 0.44; boiled = 0.36; steamed = 0.40; boiled with salt = 0.37	Purwaningsih et al., 2015
Scallop	mix	Steamed and fried	–	Fresh = 21.02; steamed = 20.95; fried = 1.73	–	Fresh = 1.00; steamed = 1.00; fried = 1.07	Wright et al., 2018
Australian scallop	*Pecten fumatus*	Steamed, deep-fried in batter and pan fried (vegetable oil)	–	Fresh = 19.94; steamed = 23.39; deep-fried in batter = 14.46; pan fried (vegetable oil) = 18.06	Fresh = 6.81; steamed = 7.04; deep-fried in batter = 3.35; pan fried (vegetable oil) = 5.36	Fresh = 1.31; steamed = 1.46; deep-fried in batter = 1.56; pan fried (vegetable oil) = 1.48	Su and Babb, 2007
Veined rapa whelk	*Rapana venosa*	Boiled	Fresh = 5.10; boiled = 6.22	Fresh = 19.95; boiled = 17.81	Fresh = 1.43; boiled = 1.35	Fresh = 0.95; boiled = 0.93	Merdzhanova et al., 2018
Disk abalone	*Haliotis discus*	Heating in water bath at 60–100 °C for 2 h	–	Fresh = 14.74; 60 °C = 15.67; 70 °C = 17.22; 80 °C = 16.32; 90 °C = 16.00; 100 °C = 15.88	Fresh = 0.89; 60 °C = 1.03; 70 °C = 1.03; 80 °C = 1.00; 90 °C = 1.00; 100 °C = 0.94	Fresh = 0.76; 60 °C = 0.83; 70 °C = 0.87; 80 °C = 0.81; 90 °C = 0.77; 100 °C = 0.82	Wang et al., 2014
Channeled apple snail	*Pomacea canaliculata*	Boiled, steamed and boiled with salt	Fresh = 4.38; boiled = 1.24; steamed = 2.70; boiled with salt = 1.24	Fresh = 8.00; boiled = 5.84; steamed = 7.75; boiled with salt = 5.13	Fresh = 0.82; boiled = 0.68; steamed = 0.85; boiled with salt = 0.70	Fresh = 0.78; boiled = 0.81; steamed = 0.80; boiled with salt = 0.92	Purwaningsih et al., 2015
Mud creeper	*Cerithide obtusa*	Boiled, steamed and boiled with salt	Fresh = 4.71; boiled = 1.81; steamed = 2.26; boiled with salt = 1.76	Fresh = 5.34; boiled = 2.71; steamed = 3.16; boiled with salt = 1.81	Fresh = 0.84; boiled = 0.68; steamed = 0.71; boiled with salt = 0.67	Fresh = 1.81; boiled = 1.72; steamed = 2.03; boiled with salt = 1.17	Purwaningsih et al., 2015
Crayfish	*Astacus leptodactylus*	Boiled, sous vide cooked and microwaved	Fresh = 2.55; boiled = 3.96; sous vide cooked = 3.89; microwaved = 4.00	Fresh = 12.06; boiled = 8.76; sous vide cooked = 11.77; microwaved = 10.45	Fresh = 0.88; boiled = 0.87; sous vide cooked = 0.95; microwaved = 0.84	Fresh = 0.68; boiled = 0.53; sous vide cooked = 0.74; microwaved = 0.74	Ozturan et al., 2022

(*continued on next page*)

Table 2 (*continued*)

Common name	Species	Cooking methods	Total lipid (% DW)	EPA + DHA (%)	n3/n6	PUFA/SFA	References
Shrimp	*Penaeus vannamei*	Boiled, grilled and microwaved	–	Fresh = 35.92; boiled = 39.25; grilled = 41.00; microwaved = 41.41	–	Fresh = 1.88; boiled = 2.10; grilled = 2.19; microwaved = 2.22	Wang et al., 2022
Green tiger prawn	*Penaeus semisulcatus*	Salted, fried, grilled and boiled	Fresh = 14.30; salted = 12.28; fried = 19.92; grilled = 14.90; boiled = 15.33	–	Fresh = 2.44; salted = 2.38; fried = 1.64; grilled = 2.38; boiled = 2.50	Fresh = 1.45; salted = 1.45; fried = 1.63; grilled = 1.42; boiled = 1.44	AlFaris et al., 2022
White shrimp	*Penaeus setiferus*	Fried (sunflower oil)	Fresh = 0.40; fried = 39.78	Fresh = 23.02; fried = 2.73	Fresh = 1.49; fried = 0.05	Fresh = 1.11; fried = 6.13	Czech et al., 2015

DW = dried weight.

Table 3
The effects of refrigeration storage on the lipid nutritional quality of fish and shellfish.

Common name	Species	Condition	Storage	Total lipid (% DW)	EPA + DHA	n3/n6	PUFA/SFA	References
Atlantic salmon	*Salmo salar*	Hot-smoked fillet	4 °C for 28 days	–	0D = 12.4; 7D = 11.5; 14D = 11.6; 21D = 11.7; 28D = 11.8	–	–	Bienkiewicz et al., 2022
Atlantic salmon	*Salmo salar*	Cold smoked fillet	4 °C for 28 days	–	0D = 14.8; 7D = 14.0; 14D = 13.8; 21D = 13.9; 28D = 13.7	–	–	Bienkiewicz et al., 2022
Atlantic salmon	*Salmo salar*	Fillet	4 °C for 28 days	–	0D = 15.2; 7D = 13.9; 14D = 13.3; 21D = 12.8; 28D = 12.2	–	–	Bienkiewicz et al., 2022
Atlantic markerel	*Scomber scombrus*	Fillet	2–4 °C for 24 days	0D = 6.09; 6D = 6.06; 12D = 5.56; 24D = 5.67	0D = 1.62; 6D = 1.59; 12D = 1.38; 24D = 1.40	–	0D = 1.27; 6D = 1.27; 12D = 1.21; 24D = 1.20	Sardenne et al., 2021
whelk	*Neverita didyma*	flesh without shell	4 °C for 10 days	–	0D = 32.19; 2D = 32.29; 4D = 33.26; 6D = 30.82; 8D = 30.71; 10D = 32.18	0D = 2.42; 2D = 2.41; 4D = 2.50; 6D = 2.73; 8D = 2.37; 10D = 2.62	0D = 2.35; 2D = 2.36; 4D = 2.64; 6D = 2.01; 8D = 2.09; 10D = 2.13	Yu et al., 2020
whelk	*Neptunea arthritica cumingi* Crosse	flesh without shell	4 °C for 10 days	–	0D = 19.08; 2D = 16.82; 4D = 19.51; 6D = 17.24; 8D = 22.11; 10D = 20.21	0D = 1.59; 2D = 1.43; 4D = 1.65; 6D = 1.59; 8D = 1.69; 10D = 1.64	0D = 2.54; 2D = 2.52; 4D = 2.43; 6D = 2.26; 8D = 2.33; 10D = 2.28	Yu et al., 2020
Blue mussel	*Mytilus edulis*	flesh without shell	4 °C for 4 days	–	0D = 40.41; 1D = 40.68; 2D = 39.09; 3D = 40.18; 4D = 37.89	0D = 7.74; 1D = 7.14; 2D = 6.14; 3D = 7.08; 4D = 5.56	0D = 1.96; 1D = 2.09; 2D = 2.04; 3D = 2.02; 4D = 2.00	Zhou et al., 2019
catfish	*Arius maculatus*	Whole fish	4 °C for 9 days	–	0D = 12.46; 3D = 9.28; 6D = 7.36; 9D = 6.60	0D = 1.73; 3D = 1.50; 6D = 1.33; 9D = 1.56	0D = 0.55; 3D = 0.52; 6D = 0.41; 9D = 0.33	Tenyang et al., 2017
Sardine	*Sardinella gibbosa*	Whole fish	4 °C for 15 days	–	0D = 25.84; 6D = 23.93; 15D = 23.46	0D = 4.82; 6D = 3.77; 15D = 3.61	0D = 0.78; 6D = 0.73; 15D = 0.70	Chaijan et al., 2006
Sea bass	*Dicentrarchus labrax*	Fillet	1 °C for 12 days	–	1D = 32.1; 3D = 31.4; 6D = 30.7; 9D = 32.0; 12D = 32.0	1D = 6.56; 3D = 6.62; 6D = 6.03; 9D = 6.89; 12D = 7.09	1D = 1.64; 3D = 1.64; 6D = 1.61; 9D = 1.69; 12D = 1.69	Pirini et al., 2000

DW = dried weight; D = day.

n6 ratio (-86 %) than that frying with olive oil (-75 %). However, contradictory results have been documented in a few studies, among which Sioen et al. (2006), Gladyshev et al. (2007), Domiszewski et al. (2011) and Alexi et al. (2019) did not record any significant difference in n3/n6 between fresh and fried seafood. Interestingly, Weber et al. (2008) and Zatos et al. (2013) even documented an increase in n3/n6 ratio of fried *Rhamdia quelen* (fried with canola oil), anchovy *Engraulis encrasicholus* and sardine *Sardina pilchardus* (fried with sunflower oil).

As for other cooking methods, there is no general agreement on the effects of these culinary treatments on the n3/n6 ratio of fish and shellfish. On the one hand, in food processing of fish, some studies have revealed a negative impact on the n3/n6 ratio, in the decreasing order of frying > oven cooking and boiling > microwave cooking > grilling and baking (Agren and Hanninen, 1993; Hosseini et al., 2014; Biandolino et al., 2023). In shellfish, the negative effects of cooking on n3/n6 ratio showed a decreasing order of frying > grilling > oven cooking > microwave cooking > boiling and steaming (Purwaningsih et al., 2015; Ghribi et al., 2017; Biandolino et al., 2021). However, some studies have shown that steaming (de Castro et al., 2007; Larsen et al., 2010; Zhang et al., 2013; Alexi et al., 2019), oven cooking (Koubaa et al., 2012; Alexi et al., 2019), smoking (Ljubojevic et al., 2016), boiling (Zhang et al., 2013), grilling (Bakar et al., 2008; Larsen et al., 2010) and microwave cooking (Bakar et al., 2008; Koubaa et al., 2012; Zhang et al., 2013) did not cause a significant effects on n3/n6 ratio of fish and shellfish. In fact, a few studies demonstrated that cooking increases the n3/n6 ratio of fish (Gladyshev et al., 2007; de Castro et al., 2007; Weber et al., 2008) and shellfish (Su and Babb, 2007; Purwaningsih et al., 2015).

For short-term refrigeration storage at 4 °C, Yu et al. (2020) demonstrated that the n3/n6 ratio of whelk *Neverita didyma* and *Neptunea arthritica cumingi Crosse* without shell did not significantly change within 10 days of storage. However, the n3/n6 ratio of blue mussel *Mytilus edulis* (without shell) (Zhou et al., 2019), catfish *Arius maculates* (whole fish) (Tenyang et al., 2017), sardine *Sardinella gibbosa* (whole fish) (Chaijan et al., 2006) and sea bass *Dicentrarchus labrax* (Pirini et al.,

Table 4
The effects of frozen storage on the lipid nutritional quality of fish and shellfish.

Common name	Species	Condition	Storage	Total lipid (% DW)	EPA + DHA	n3/n6	PUFA/SFA	References
Herring	*Clupea harengus*	dark muscle	−25 °C for 5 months	–	0 M = 20.70; 2 M = 18.67; 3.5 M = 12.31; 5 M = 20.16	–	0 M = 1.21; 2 M = 1.08; 3.5 M = 0.67; 5 M = 1.18	Dang et al., 2018
Herring	*Clupea harengus*	light muscle	−25 °C for 5 months	–	0 M = 22.93; 2 M = 22.65; 3.5 M = 19.90; 5 M = 21.80	–	0 M = 1.25; 2 M = 1.20; 3.5 M = 1.07; 5 M = 1.16	Dang et al., 2018
Hoki	*Macruronus novaezelandiae*	light muscle	−20 °C and −30 °C for 18 months	–	0D = 45.83; −20 °C after 18 months = 39.55; −30 °C after 18 months = 44.44	0D = 17.61; −20 °C after 18 months = 15.86; −30 °C after 18 months = 16.14	0D = 1.95; −20 °C after 18 months = 1.72; −30 °C after 18 months = 1.75	Karlsdottir et al., 2014
Saithe	*Pollachius virens*	light muscle	−20 °C and −30 °C for 18 months	–	0D = 54.78; −20 °C after 18 months = 47.16; −30 °C after 18 months = 54.21	0D = 19.40; −20 °C after 18 months = 17.98; −30 °C after 18 months = 20.34	0D = 2.51; −20 °C after 18 months = 2.34; −30 °C after 18 months = 2.44	Karlsdottir et al., 2014
Red tilapia	*Oreochromis niloticus* × *Tilapia mosambicus*	Fillet	−18 °C for 150 days	–	0D = 7.58; 2D = 6.72; 30D = 5.67; 60D = 4.92; 90D = 4.21; 120D = 4.22; 150D = 3.72	0D = 0.59; 2D = 0.57; 30D = 0.51; 60D = 0.49; 90D = 0.46; 120D = 0.47; 150D = 0.49	0D = 1.23; 2D = 1.16; 30D = 1.08; 60D = 1.07; 90D = 0.91; 120D = 0.89; 150D = 0.20	Karami et al., 2013
Atlantic hake	*Merluccius hubbsi*	High oxygen permeability packed fillet	−18 °C for 120 days	0D = 8.3; 30D = 9.0; 60D = 10.0; 90D = 10.9; 120D = 11.7	0D = 26.89; 30D = 24.35; 60D = 22.15; 90D = 19.40; 120D = 17.78	0D = 5.00; 30D = 5.90; 60D = 5.76; 90D = 5.56; 120D = 5.70	0D = 1.55; 30D = 1.31; 60D = 1.12; 90D = 0.90; 120D = 0.78	Saldanha and Bragagnolo, 2008
Atlantic hake	*Merluccius hubbsi*	Low oxygen permeability packed fillet	−18 °C for 120 days	0D = 8.6; 30D = 9.0; 60D = 9.4; 90D = 9.9; 120D = 10.4	0D = 21.89; 30D = 20.68; 60D = 19.07; 90D = 17.92; 120D = 16.43	0D = 5.27; 30D = 5.52; 60D = 5.44; 90D = 5.56; 120D = 5.74	0D = 1.07; 30D = 0.96; 60D = 0.83; 90D = 0.74; 120D = 0.64	Saldanha and Bragagnolo, 2008
Australian scallop	*Pecten fumatus*	–	−20 °C for 22 days	–	Fresh = 19.94; frozen = 18.97	Fresh = 6.81; frozen = 6.75	Fresh = 1.31; frozen = 1.13	Su and Babb, 2007
Common carp	*Cyprinus carpio*	Fillet with skin	−20 °C for 45 days	–	0D = 0.7; 15D = 1.3; 30D = 1.5; 45D = 1.2	–	0D = 1.13; 15D = 0.99; 30D = 0.57; 45D = 0.80	de Castro et al., 2007
Tambacu	*Colossoma macropomum* x *Piaractus mesopotamicus*	Fillet without skin	−20 °C for 45 days	–	0D = 9.7; 15D = 4.4; 30D = 7.0; 45D = 7.5	–	0D = 0.82; 15D = 0.63; 30D = 0.49; 45D = 0.66	de Castro et al., 2007
Nile tilapia	*Oreochromis niloticus*	Fillet without skin	−20 °C for 45 days	–	0D = 5.6; 15D = 3.8; 30D = 4.2; 45D = 7.9	–	0D = 0.38; 15D = 0.36; 30D = 0.45; 45D = 0.59	de Castro et al., 2007
Common carp	*Cyprinus carpio*	Fillet without skin	−20 °C for 45 days	–	0D = 1.7; 15D = 4.1; 30D = 1.3; 45D = 1.6	–	0D = 1.08; 15D = 1.10; 30D = 0.58; 45D = 0.75	de Castro et al., 2007
Nile tilapia	*Oreochromis niloticus*	Fillet with skin	−20 °C for 45 days	–	0D = 4.5; 15D = 2.7; 30D = 3.1; 45D = 4.4	–	0D = 0.36; 15D = 0.32; 30D = 0.35; 45D = 0.43	de Castro et al., 2007
Tambacu	*Colossoma macropomum* x *Piaractus mesopotamicus*	Fillet with skin	−20 °C for 45 days	–	0D = 1.8; 15D = 1.8; 30D = 3.0; 45D = 4.2	–	0D = 0.48; 15D = 0.47; 30D = 0.42; 45D = 0.48	de Castro et al., 2007

DW = dried weight; D = day; M = month.

2000) significantly decreased after 1–6 days of refrigeration storage. In longer term frozen storage, the optimum storage period largely depends on storage temperature. At the frozen storage temperature of −18 °C to −20 °C, the n3/n6 ratio of red tilapia *Oreochromis niloticus* × *Tilapia mosambicus* fillets (Karami et al., 2013) and Australian scallop *Pecten fumatus* (Su and Babb, 2007) significantly decreased after 30 days and 22 days, respectively. At temperature of −30 °C, Karlsdottir et al. (2014) demonstrated that the n3/n6 ratio of hoki *Macruronus novaezelandiae* and saithe *Pollachius virens* did not change significantly for 18 months.

5. Effects of food processing on the PUFA/SFA of fish and shellfish

Saturated fatty acids (SFA), especially myristic acid (C14:0) and palmitic acid (C16:0), have been shown to increase low-density lipoprotein (LDL) cholesterol, and reducing SFA consumption has been shown to reduce the risk of coronary heart disease (Mozaffarian et al., 2010). In fact, Pigsborg et al. (2022) have shown that increasing PUFA/SFA ratio in the diet through replacing SFA with n-6 LC-PUFA is associated with a reduced risk of cardiovascular diseases. Therefore, the PUFA/SFA ratio is a useful indicator for evaluating the saturation of fatty acids. According to the standards of Health and Social Security, PUFA/SFA ratios of less than 0.45 are detrimental to human health (HMSO, 1994).

In general, there is no general trend in the effects of cooking on the PUFA/SFA ratio in fish and shellfish, and some studies have demonstrated that cooking does not cause significant changes in the PUFA/SFA ratio of fish (Regulska-Ilow and Ilow, 2002; Garcia-Arias et al., 2003; Sioen et al., 2006; de Castro et al., 2007; Türkkan et al., 2008; Marichamy et al., 2009; Larsen et al., 2010; Neff et al., 2014; Ljubojevic et al., 2016; Choo et al., 2018; Alexi et al., 2019) and shellfish (Purwaningsih et al., 2015; Ghribi et al., 2017; Wright et al., 2018; Merdzhanova et al., 2018; Bejaoui et al., 2019; Biandolino et al., 2021), while some other studies have shown that cooking increase the PUFA/SFA in fish (Candela et al., 1998; Echarte et al., 2001; Unusan, 2007; Gladyshev et al., 2007; Saldanha and Bragagnolo, 2008; Domiszewski et al., 2011; Musaiger and D'Souza, 2011; Koubaa et al., 2012; Neff et al., 2014; Cyprian et al., 2015; Choo et al., 2018; Brito et al., 2019; Golgolipour et al., 2019) and shellfish (Otles and Sengor, 2005; Su and Babb, 2007; Ghribi et al., 2017; Wright et al., 2018; Ozturan et al., 2022). The increase of PUFA/SFA ratio during cooking is mainly attributed to the significantly increase of PUFA (especially 18:3n-3 and 18:3n-6) compared with SFA (Musaiger and D'Souza, 2011; Brito et al., 2019) and heat induced hydrolysis of pro-atherogenic SFA (C12:0, C14:0 and C16:0) (e.g. Merdzhanova et al., 2018; Brito et al., 2019; Biandolino et al., 2021).

It is worth noting that some studies have shown that frying with olive oil, palm oil, and sunflower oil decrease the PUFA/SFA ratio of fish (Castrillion et al., 1999; Garcia-Arias et al., 2003; Marichamy et al., 2009; Zotos et al., 2013; Choo et al., 2018; Alexi et al., 2019; Biandolino et al., 2023) and shellfish (Bejaoui et al., 2019). This is due to the fact that the viscosity of these oils is higher than that of soybean oil and canola oil, thus have higher absorption rate by food during cooking (Sahasrabudhe et al., 2017; Yang et al., 2020). As a result, the higher absorption rate of cooking oil (lower PUFA/SFA ratio than seafood) leads to a decrease in the PUFA/SFA ratio of fish. In shellfish, the only one report reporting a decrease in PUFA/SFA ratio is the use of margarine to fry carpet shell *Venerupis decussata* (Bejaoui et al., 2019). The significant decrease in PUFA/SFA ratio of margarine fried clams is due to the absorption of margarine (rich in SFA, especially 16:0 and C18:0) during the frying process.

For short-term refrigeration storage, the PUFA/SFA ratio of fish and shellfish has been shown to be stable for at least 6 days at 4 °C, in which the PUFA/SFA ratio of whelk *Neverita didyma* and *Neptunea arthritica cumingi Crosse* (Yu et al., 2020), catfish *Arius maculates* (Tenyang et al., 2017), sardine Sardinella gibbosa (Chaijan et al., 2006) decreased significantly after 6 days of refrigeration storage at 4 °C. In fact, some studies did not record significant changes in the PUFA/SFA ratio of Atlantic markerel *Scomber scombrus* fillets (Sardenne et al., 2021), blue mussel *Mytilus edulis* (Zhou et al., 2019) and *Dicentrarchus labrax* (Pirini et al., 2000) for up to 24 days of refrigeration storage. Under freezing condition of −20 °C, the PUFA/SFA ratios of Atlantic hake *Merluccius hubbsi* (Saldanha and Bragagnolo, 2008), Australian scallop *Pecten fumatus* (Su and Babb, 2007) and common carp *Cyprinus carpio*, Tambacu *Colossoma macropomum* x *Piaractus mesopotamicus* (de Castro et al., 2007) decreased significantly after 30 days, 22 days and 15 days of storage, respectively. However, no significant changes in PUFA/SFA ratio of Nile tilapia *Oreochromis niloticus* (de Castro et al., 2007) and red tilapia *Oreochromis niloticus* × *Tilapia mosambicus* (Karami et al., 2013) was recorded over a period of 45 and 60 days. At a lower temperature of −25 °C, (Dang et al., 2018) demonstrated that the PUFA/SFA ratio of herring *Clupea harengus* fillets began to decrease after 2 months. However, the temperature of frozen storage may have little effect on PUFA/SFA ratio, in which Karlsdottir et al. (2014) did not record a significant difference in the PUFA/SFA ratio of hoki *Macruronus novaezelandiae* and saithe *Pollachius virens* stored at −20 °C and −30 °C for 18 months (Karlsdottir et al., 2014).

In future studies, there are some questions to be address. For the effects of food processing on lipid nutritional quality of fish and shellfish, there are still many commercially important fish and shellfish to be studied. There is also a need to further explore other technologies that can improve the oxidative stability of lipids in food (Liu et al., 2017, 2018).

6. Conclusions

In a nutshell, food processing, especially culinary preparation and cold storage, can become important approaches in monitoring the lipid nutritional quality of seafood. In general, frying has the greatest impact on the lipid content, EPA and DHA, n3/n6 ratio and PUFA/SFA ratio of seafood, and frying with margarine has the worst impact on the overall lipid nutritional quality of seafood. From the perspective of lipid nutritional quality, the most recommended cooking methods for fish and shellfish are baking and steaming, followed by boiling, grilling and microwave cooking. In terms of cold storage, the optimal short-term refrigeration storage period and longer term of frozen storage is 3 days and 2 weeks, respectively. Longer refrigeration storage period of 6 days may affect the EPA + DHA content, without compromising the n3/n6 ratio and PUFA/SFA ratio of seafood, while longer frozen period of 3 weeks may affect PUFA/SFA ratio of seafood without cause negative effect to EPA + DHA content and n3/n6 ratio. This article not only provides important information for consumers to understand the effects of food processing on the lipid nutritional quality of seafood, but also provides useful information for determining future research directions.

CRediT authorship contribution statement

Karsoon Tan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Leongseng Lim:** Project administration, Methodology. **Ya Peng:** Project administration, Methodology, Supervision, Resources. **Kit-Leong Cheong:** Visualization, Validation, Supervision.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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