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Shellfish: Nutritive Value, Health Benefits, and Consumer Safety

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Abstract: Shellfish is a major component of global seafood production. Specific items include shrimp, lobsters, oysters, mussels, scallops, clams, crabs, krill, crayfish, squid, cuttlefish, snails, abalone, and others. Shellfish, in general, contain appreciable quantities of digestible proteins, essential amino acids, bioactive peptides, long-chain polyunsaturated fatty acids, astaxanthin and other carotenoids, vitamin B_{12} and other vitamins, minerals, including copper, zinc, inorganic phosphate, sodium, potassium, selenium, iodine, and also other nutrients, which offer a variety of health benefits to the consumer. Although shellfish are generally safe for consumption, their exposure to diverse habitats, the filter feeding nature of shellfish such as oysters, clams, and mussels, and unhealthy farming and handling practices may occasionally entail health risks because of possible presence of various hazards. These hazards include pathogenic organisms, parasites, biotoxins, industrial and environmental pollutants, heavy metals, process-related additives such as antibiotics and bisulfite, and also presence of allergy-causing compounds in their bodies. Most of the hazards can be addressed by appropriate preventive measures at various stages of harvesting, farming, processing, storage, distribution, and consumption. Furthermore, consumer safety of shellfish and other seafood items is strictly monitored by international, governmental, and local public health organizations. This article highlights the nutritional value and health benefits of shellfish items and points out the various control measures to safeguard consumer safety with respect to the products.

Keywords: consumer safety, health benefits, nutritive value, proximate composition, shellfish

Introduction

Shellfish is a major component of our global aquatic food supply. Shellfish consists broadly of 2 types of animals, crustaceans and mollusks. Crustaceans are invertebrates with segmented bodies, protected by hard shells made of chitin, and include shrimp, lobster, crayfish, crab, and krill. Mollusks are invertebrates with soft bodies, divided into foot and visceral section. They are subdivided into bivalves, cephalopods, and gastropods. The commercially important bivalves are mussels, oysters, clams, and scallops, while cephalopods include squid, cuttlefish, and octopus. The gastropod group contains abalone, sea snail, cockle, and whelks, among others. It is estimated that the ocean is inhabited by more than 1000 species of crustaceans, 50000 species of mollusks, besides 13000 species of finfish (Nybakken 2001). Information on the nutritive value of shellfish is generally scattered in the literature and often only discuss composition of general seafood items, particularly finfish products. This article is intended to compile this information and discuss recent data on the proximate compositions of different shellfish items, and to evaluate the health benefits of individual constituents. Shellfish may be prone to various hazards arising from their habitats and also due to other reasons. The article also briefly describes these hazards and measures to control these hazards. The roles of various regulatory agencies to ameliorate these hazards in order to ensure consumer safety are also pointed out.

Availability, Handling, and Consumption of Shellfish

Global production

According to the State of World Fisheries and Aquaculture, published by the United Nation's Food and Agriculture Organization (FAO), in 2014, an amount of 167.2 million metric tons (MMT) of seafood was globally available, with landings of shrimp, American lobsters, and cephalopods at 3.5, 0.16, and 4.3 MMT, respectively (FAO 2016). In recent times, the seafood industry is facing challenges, such as concerns about sustainability, slow stagnation of capture fisheries, rising consumer demand, and overall safety of the products. The landing of shrimp, one of the major shellfish commodities, has been stable since 2012 (FAO 2016). American lobster (*Homarus americanus*) and Norway lobster (*Nephrops norvegicus*) have accounted for more than 60% of world lobster availability, the former reaching a record catch of 160000 tons in 2014. Cephalopods are fast-growing short-lived shellfish; squid is the main component of the cephalopods, followed by cuttlefish, and octopus. The argentine short fin squid (*Illex argentinus*) and the jumbo flying squid (*Dosidicus gigas*) are the most commercially landed squid species. Since 2008, catches of cuttlefishes and octopuses have remained relatively stable at 300000 and 350000 tons, respectively. The common octopus (*Octopus vulgaris*), and the cuttlefish (*Sepia* spp.) remain overfished. The Pacific oyster

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(*Crassostrea gigas*) is an invasive species most fecund of all oysters. The eastern oyster (*Crassostrea virginica*) is moving progressively toward overfishing (FAO 2016).

Consumer demand for shellfish and other seafood has resulted in a significant rise in their aquaculture in fresh, brackish, and marine waters, with a total production of 73.8 MMT in 2014, at an estimated value of U.S.$ 160 billion. This included 16.1 MMT of mollusks composed of 104 species valued at U.S.$ 19 billion, and 6.9 MMT of crustacean valued at U.S.$ 36.2 billion (FAO 2016). The white leg shrimp or the Pacific white shrimp (*Litopenaeus vannamei*) and the freshwater prawn *Macrobrachium rosenbergii* cultured both in fresh water as well as brackish water are the most farmed crustaceans. In addition, other popular shellfish such as black tiger prawn (*Penaeus monodon*), scallop (*Pecten yesoensis*), squids (*Loligo duvauceli, Doryteuthis sibogae,* and *Sepioteuthis* spp.), and the cuttlefishes (*Sepia pharaonis, Sepia aculeate, Sepia officinalis,* and *Sepia elliptica*) are farmed mainly in Asian countries (FAO 2016). Abalones (*Haliotis* spp.) are commercially farmed in China (Lou and others 2013). In the past 40 y, the world abalone supply has increased 5-fold owing primarily to increased abalone farming practices (Suleria and others 2017). The Japanese carpet shell or Manila clam (*Ruditapes philippinarum*), Yesso scallop (*Patinopecten yessoensis*), blue mussel (*Mytilus edulis*), Asian green mussel (*Perna viridis*), green-lipped mussel (*P. canaliculus*), the scallop (*P. yessoensis*), crab (*Scylla serrata*), and the clam (*Anadara granosa*) are other farmed shellfish items (Kim and Venkatesan 2015). Aquaculture is projected to grow at almost 39% annually, with an estimated production of about 102 MMT in 2025 (FAO 2016).

General handling and processing of shellfish

Freshly harvested shellfish are highly perishable and require care during handling, processing, and storage; the handling and preprocessing steps vary with the species (Su and Liu 2013). Shellfish, upon landing, need to be immediately cleaned, washed, and subjected to depuration, beheading, peeling, deveining, and other operations, depending on the items. Molluscan shellfish such as oysters, clams, and mussels, which filter enormous quantities of water, accumulate microorganisms and other particulate matter in their bodies. They are immediately decontaminated by depuration by holding them in excess of water for a couple of days, which reduces their microbial load (Bindu and Joseph 2005). Oysters are initially washed with water to remove mud. The washed oysters are exposed to steam in special retorts or heated by infrared heating to open the shells, which are shucked (Martin and Hall 2006). Washed lobsters are transported in ice, their claws generally kept tied to prevent injury among the animals. Cephalopods, being highly perishable, should not be exposed to direct sunlight or wind, and should be carefully cleaned, and quickly iced or frozen (Kreuzer 1984). Shrimp are prepared as whole-head on, headless-shell-on, peeled with or without deveining, cut as fan-tail or butterfly for freezing (Chandrasekharan 1994).

Chilling in ice is the most common postharvest processing operation. It extends shelf-life by a few days depending on the shellfish (Venugopal 2006; Gokoglu and Yerlikaya 2015). The shelf-life of chilled products is evaluated in terms of sensory, chemical, microbiological, and physical parameters (Ashie and others 1996; Huss and others 2003). The decrease in the content of anserine (and also other dipeptides including carnosine and glutathione) could be a freshness index for chilled lobster (Ruiz-Capillas and Moral 2004). Most temperate shellfish like shrimp, scampi, abalone, scallop, and clam have chilled shelf-life ranging from 6 to 10 d, while their warm water counterparts remain acceptable in ice for 8 to 12 d (Ashie and others 1996; Huss and others 2003). Chilled storage life of whole squid and cuttlefish are 9 and 10 d, respectively (Vaz-Pires and others 2004; Tantasuttikul and others 2011). The common octopus (*O. vulgaris*) and the adductor muscle of Pacific lions-paw scallop have a chilled storage life of 8 and 12 d, respectively (Pacheco-Aguilar and others 2008). Muscle autolysis is the main reason for spoilage of cephalopods (Vaz-Pires and others 2004). The main defect in cold-stored shrimp, lobster, and scallop is oxidation of polyphenols resulting in a darkening of the flesh, known as "black-spot" formation, which occurs within a few hours after harvest (Nirmal and others 2015). In lobster, fat oxidation may cause yellow spots; blue discoloration occurs in crabmeat as a result of the breakdown of the copper-containing oxygen-carrying protein hemocyanin (Huss and others 2003).

Freezing by chilled air or cryogens such as liquid nitrogen is commercially employed for international trade of high-value shellfish such as shrimp, lobsters, and cephalopods (Chandrasekharan 1994; Venugopal 2006; Gokoglu and Yerlikaya 2015). Quality losses upon prolonged frozen storage are due to changes in texture, protein functionality, lipid oxidation, flavor changes, and drip formation during thawing (Venugopal 2006). The process of individually quick-freezing (IQF) allows rapid freezing of shellfish in convenient, ready-to-cook quantities. Shrimp, scampi tail meat, squid fillets (mantle), squid rings, and scallops are materials for the IQF process. Popular IQF bivalve products include vacuum-packed half shell oysters, clams, cockles, and scallops, which may also be coated with bread crumbs prior to freezing (Venugopal 2006). Apart from freezing, shellfish are subjected to thermal (blanching, boiling, grilling, steaming, pressure cooking, frying, roasting, baking, canning), dehydration (air, vacuum, freeze-drying), breading, high hydrostatic pressure (HHP), modified atmosphere packaging (MAP), and other treatments (Kreuzer 1984; Venugopal 2006). Combination-treatments can offer consumer-friendly products. A few examples are cited. Mussel in sauce is vacuum sealed, cooked, cooled, and frozen to give a shelf-life up to 2 y (Venugopal 2006). A cook-chill process for peeled shrimp (*Penaeus indicus*) consists of dipping in 10% brine containing 5% sodium tri-polyphosphate followed by steaming the salted product for 10 min and packaging. The product has a shelf-life of up to 25 d at 3 ± 0.5 °C (Venugopal 1993). Oysters can be preserved by a combination of cold pasteurization and HHP treatment (Muth and others 2013)

Consumption pattern of shellfish

The demand for seafood is rapidly rising all over the world, driven by increases in populations and their rising purchasing power. According to a recent survey, the leading drivers of seafood consumption are nutrition, taste, and convenience, while the main barriers are price, availability, and concern about quality (Christensen and others 2017). In 2014, an amount of 146.3 MMT of seafood was used as human food, giving a global per capita seafood consumption of 20.1 kg, contributing to about 20% of total average per capita intake of animal protein. The per capita shellfish consumption in 2013 was 4.9 kg, subdivided into 1.8 kg of crustaceans, 0.5 kg of cephalopods, and 2.6 kg of other mollusks (FAO 2016). A recent survey reported per capita seafood consumption of 25.8 and 35 kg in the European Union (EU) and southern Europe, respectively (Megapesca (Portugal) 2017). Consumers' interests in shellfish products encompass fresh items, eaten raw, or minimally processed, to variously prepared (salted, smoked, coated, canned) and ready-to-eat items (Venugopal 2006). The global demand for shellfish is indicated by trade figures, which showed that, while shellfish, in quantity terms, formed 38% of

Table 1–Protein, fat, cholesterol, PUFA contents, and amino acid score (AAS) of shellfish.

	Source A (samples cooked under moist heat)					Source B (raw edible portions)					Source C (raw edible portions)
Shellfish	I	II	III	IV	V	I	II	III	IV	V	V
Shrimp, mixed	20.9	113	1.1	195	211	22.8	–	1.7	211	590	480
Prawn (cold)[a]	15.4	–	0.9	143	–	–	–	–	–	–	–
Prawn (warm)[a]	17.6.	–	0.7	–	–	–	–	–	–	–	–
Oyster, mixed	18.8	107	3.6	90	1480	11.4	–	3.4	79	1056	690
Oyster, eastern	14.0	107	4.9	105	1345						
Squid, mixed species	15.6	108	2.0	221	549	17.9	–	1.4	233	524	490
Mussel, blue	24.0	107	4.5	56	866	23.8	–		56	1212	440
Lobster, northern	21.0	113	0.6	72	866	19.0	–	0.9	146	–	370
Crab, Dungeness	19.0	113	1.1	65	300	22.3	–	1.2	76	407	310
Crab, blue	20.2	107	1.8	100	549	–	–	–	–	–	320
Crab, Alaska king	19.4	113	1.5	53	636		–	–	–	–	–
Crab, white meat, cooked[a]	20.5	–	0.3	66	80	–	–	–	–	–	–
Scallop, mixed species, raw	17.0	107	0.8	33	300		–	–	–	222	220
Scallop, bay and sea	23.2	–	1.4	53	196	20.5	–			–	–
Clam, mixed species	25.5	107	1.9	67	396	–	–	–		–	140
Crayfish, mixed	16.6	113	1.2	133	194	16.8	–	1.2		367	–
Cuttlefish	32.5	107	1.4	224	224	32.4	–	1.4	224	268	225

[a] Prawn (cold water), *P. borealis*, cooked; prawn (warm water), *P. vannamei*, raw, Department of Health, UK (2013).
Columns: I, protein; II, Amino Acid Score (AAS); III, crude fat; IV, cholesterol; and V, total PUFA. Values are given as g/100 g, w. wt. for protein and fat; and mg/100 g, w. wt. for cholesterol and PUFA.
A, SELFNutritionData; B, USDA (2012); C, Dong (2001); -, not reported.

total seafood traded in 2013; in terms of value recovered, its contribution was 63.7% (FAO 2016).

Shrimp, consisting of over 300 species, is the most popular shellfish due to its unique texture and color. Consumers generally prefer light gray or gray-colored raw shrimp, and brightly orange-colored cooked shrimp (Parisenti and others 2011). In the United States, per capita shrimp consumption of about 1.73 kg was recorded in 2012; almost 90% of the shrimp consumed coming from imports (Reed and Royales 2014). Bivalves are characteristically tender and easily digested, which make them attractive to the consumers. The major commercial bivalve species include the soft-shelled as well as hard-shelled clams, blue mussel, eastern oyster, and sea scallop. The consumption of marine mussels has increased steadily over the past decades (Grienke and others 2014). Japan, Korea, Argentina, Taiwan, Japan, China, and Spain consume cephalopods in significant quantities (Vaz-Pires and others 2004; Kim and Venkatesan 2015). Popular cephalopods include the common cuttlefish (*S. officinalis*), European squid (*Loligo vulgaris*), common octopus (*O. vulgaris*), and the musky octopus (*Eledone moschata*) (Ozogul and others 2008; FAO 2016).The popular crabs include *Portunus* spp., *Charybdis* spp., *Chionocetes* spp., the mud crab (*S. serrata*), the Dungeness crab (*Metacarcinus magister*), and the brown crab (*Cancer pagurus*) (Maulvault and others 2012; Kim and Venkatesan 2015). The shellfish species consumed in Europe are oysters, mussels, king scallops, lobsters, winkles, whelks, cockles, clams, crab, and others (Ruiz-Capillas and Moral 2004; Barrento and others 2009a, 2009b; Guéguen and others 2011). Marine snail (*Hexaplex trunculus*) is popular in northern African countries (Zarai and others 2011). Antarctic krill (*Euphausia superba*) is distributed around the South Pole; about 500000 tons are harvested annually by the USSR and Japan (Gigliotti and others 2008). There is recent commercial interest in abalone because it is a culinary delicacy, besides having therapeutic value (Suleria and others 2017).

The consumer interest in various shellfish, as indicated above, makes significant contribution to food security. It has been recognized that food security, nutrition, and food safety are inextricably linked (World Health Organization, WHO 2015). As Jennings and others (2016) pointed out, aquatic food security demands that the seafood supply should not only be sustainable to meet the needs and preferences of people, but the products are also required to provide them nutritional benefits while posing minimal health risks. The proximate compositions of various shellfish and their health benefits are discussed in the following.

Proximate Composition of Shellfish

Proximate compositions of shellfish, and also those of finfish are provided in databases. The global FAO/INFOODS database contains proximate compositions of raw or cooked portions of 152 crustaceans and 114 mollusks (FAO/INFOODS 2016).The database of U.S. Dept. of Agriculture (USDA) contains about 3000 raw and processed food items including shellfish (USDA 2012). Data on proximate compositions of shellfish have also been provided by the U.S. National Marine Fisheries Service (NMFS 1987), the Dept. of Health, UK (2013), and the Food Standards Australia and New Zealand (FSANZ 2011). Other sources include Nettleton and Exler (1992), Venugopal and Shahidi (1996), Gopakumar (1997), Dong (2001), Venugopal (2006), and Souci and others (2008). The major components of shellfish are the following.

Proteins

In general, shellfish has higher protein contents than finfish. Unlike vertebrates, raw shellfish muscle, in addition to myosin and other myofibrillar proteins, also contains the protein, paramyosin up to 19% (w/w), which is rich in glutamic acid. Paramyosin, which has a molecular weight up to 258 kDa, is found in striated and smooth muscle of invertebrates, and is involved in catch contraction (Venugopal and Shahidi 1996). The reported average protein contents (g/100 g raw meat) of various shellfish vary: shrimp, 17.0 to 22.1; scallop, 14.8 to 17.7; squid, 13.2 to 19.6; crab, 15.0 to 18.4; lobster, 18.2 to 19.2; krill, 12.0 to 13.0; clam, 9.0 to 13.0; mussel, 12.6 to 13.0; cuttlefish, 16.6 to 17.3; and oyster, 8.9 to 14.3 (NMFS 1987; Venugopal and Shahidi 1996; Gopakumar 1997; Dong 2001; Souci and others 2008; USDA 2012). Table 1 (Source A, Column 1) provides protein contents of shellfish items cooked under moist heat. It may be noted from the Table 1 that samples cooked under moist heat have good protein contents. Protein contents of some raw shellfish species from Indian waters vary from 14.0% to 21.6% (Table 2).

Protein contents of shellfish have also been reported in recent studies. Edible portions of the Asian hard clam had 9% to 12.75%

Table 2–Proximate composition of some shellfish species from Indian waters.

Shellfish	Scientific name	Moisture (%)	Protein (%)	Crude fat (%)	Ash (%)
Blood clam	*Anadara granosa*	81.4	14.5	1.8	0.8
Speckled shrimp	*Metapenaeus monoceros*	77.4	20.0	0.7	2.1
Backwater clam	*Meretrix casta*	71.5	15.7	2.0	2.1
Crab	*Scylla serata*	79.2	17.5	0.2	1.6
Cuttlefish	*Sepia* spp.	75.8	18.1	0.2	1.4
Giant freshwater prawn	*Macrobrachium rosenbergii*	78.3	21.2	0.3	0.4
Prawns, cold water (cooked)	*Pandalus borealis*	82.4	16.0	0.4	1.9
Indian white shrimp	*Penaeus indicus*	77.4	20.9	0.6	1.4
Green mussel	*Perna viridis*	76.7	12.6	2.6	2.1
Lobster, flathead	*Thenus orentalis*	75.6	21.6	0.6	2.3
Squid	*Logio spp.*	75.0	19.9	0.9	0.5
Antarctic krill	*Euphasia superba*	84.7	13.0	7.0	3.0

Source: Adapted from Gopakumar (1997).

proteins. Myofibrillar proteins were the major fractions of foot and mantle of the clam, constituting 31% to 40% (Karnjanapratum and others 2013). The breast, claw meat, and hepatopancreas of the blue crab have about 19% protein, w. wt. (Küçükgülmez and others 2006). Generally, chemical composition of brown meat (tissue in the body cavity comprised mainly gonads and hepatopancreas) differed significantly from muscle (white meat in claws and legs) of crabs (Maulvault and others 2012). The crude protein contents of claw meat and hepatopancreas of the green crab (*C. mediterraneus*) were 17.8% to 18.2% and 13% to 14%, respectively (Cherif and others 2008). The meat of white shrimp had higher protein contents than that of black tiger shrimp; the former having higher amounts of stromal proteins with greater pepsin-soluble collagen (Sriket and others 2007). The raw meat of brown shrimp (*Crangon crangon*) from the Black sea has a protein content of about 18.5% (Turan and others 2011). Marine snail meat and hepatopancreas are important sources of protein (Zarai and others 2011). The edible portion of common octopus (*O. vulgaris*) has appreciable level of proteins (Vaz-Pires and others 2004).

Free amino acids

Free amino acids (FAAs) constitute an important fraction of nonprotein nitrogenous compounds in shellfish muscle. Crustaceans have a high content of amino acids in comparison with finfish. The amino acids alanine, glutamic acid and glycine are greatly responsible for the flavor of cooked shellfish. Alanine and glycine contribute to sweet tastes, and glutamic acid to the "umami" taste typical of crustaceans (Huss and others 2003). Shrimp has good contents of glycine (up to 1% of the fresh muscle), alanine, and proline (NMFS 1987). Muscle tissues of both white and black shrimp contain arginine, leucine, isoleucine, and proline. The major essential amino acids (EAAs) of red and pink shrimp are arginine, lysine, leucine, and methionine, while the non-EAAs are glutamic acid, aspartic acid, proline, and glycine (Rosa and Nunes 2004). Glutamic acid and glycine contents were greater in black tiger shrimp meat, while white shrimp had good levels of hydroxproline. Arginine, leucine, isoleucine, and proline were predominant in both shrimps (Sriket and others 2007). The brown shrimp has high contents of EAAs, namely, leucine, iso-leucine, valine, and lysine, while non-EAAs were aspartic acid, glutamic acid, glycine, and alanine (Turan and others 2011). The Norway lobster has EAAs, namely, threonine, leucine, valine, lysine, and arginine, each at levels of 40 mg% of raw meat. It has also the non-EAAss glycine, alanine, and glutamic acid at 57.9, 57.2, and 31.2 mg%, respectively. In addition, it also contains the dipeptide, anserine at 53 mg% in the raw meat (Rosa and Nunes 2004; Ruiz-Capillas and Moral 2004). Edible portions of Asian hard clam contains up to 188 mg of EAAs per gram, dominated by leucine and lysine (Karnjanapratum and others 2013). Glycine is the dominant amino acid in the thick shell mussel (*Mytilus coruscus*), while lysine, threonine, phenylalanine, and arginine are the important EAAs (Li and others 2010a). Edible tissues of the marine snail are good sources of EAAs, particularly aspartic acid (Zarai and others 2011). Green crab meat is well balanced in EAA contents, except for tryptophan (Naczk and others 2004). The contents of taurine (2-aminoethane sulfonic acid) in the muscle of mussel, oyster, cuttlefish, and squid vary between 7.5% and 11.9% of total amino acids (Suseela Mathew, 2016 May 5. personal communication).

Lipids

Shellfish items have low crude lipid contents, generally up to 2% (w/w), as shown in Table 1. The lipid contents of several shellfish from Indian waters also have very low lipid contents (Table 2). Shellfish lipids have appreciable proportions of n-3 (omega-3) long-chain polyunsaturated fatty acids (PUFAs), particularly eicosapentaenoic acid (EPA) (*cis*-5,8,11,14,17, C20:5), and docosahexaenoic acid (DHA) (*cis*-4,7,10,13,16,19, C22:6). Generally, the contents of PUFA are higher than those of saturated fatty acids (SFAs), and monounsaturated fatty acids (MUFAs) (Berge and Barnathan 2005). The contents of EPA and DHA in shellfish usually range between 300 and 500 mg%, raw muscle); their contents are generally lower than those of oily finfish such as Atlantic mackerel, salmon, and sardine (Dong 2001; Hossain and Takahashi 2012). Passi and others (2002) reported that 3 species of cephalopods and 6 species of crustaceans (and also teleosts) from the Mediterranean Sea have higher contents of *n*-3 PUFA (16.6% to 57.1%) than the n-6 PUFA (4.1% to 10.6%); all of the species showing an *n*-3 to *n*-6 ratio of more than 1. Besides, total PUFAs (21.7% to 61.5%) were the highest, followed by SFA (16.9% to 41.3%) and MUFA (9.1% to 42.8%). The Mediterranean giant red shrimp (*Aristaeomorpha foliacea*) has good levels of n-3 PUFA, particularly EPA and DHA (Bono and others 2012). Korean shellfish species are rich in EPA and DHA and are low in MUFA (Surh and others 2003).

The lipids of the shrimp spp. (*Parapenaeus longirostris* and *Aristeus antennatus*), and Norway lobster (*N. norvegicus*) contain 42% to 48% PUFA, 26% to 35% MUFA, and 23% to 27% SFA (Rosa and Nunes 2004). The crude fat (1%, w/w) of brown shrimp (*C. crangon* L) meat consisted of 33% SFA, 22% MUFA, and 29% n-3 PUFA. The SFA and MUFA fractions have 21% palmitic acid and 14% oleic acid, respectively. The PUFA consisted of EPA and DHA at 41% and 32%, respectively (Turan and others 2011). The n-3 PUFA of white shrimp (*Peneaus vannamei*) and black tiger shrimp (*P. monodon*) are 42% to 44% of crude lipids. PUFAs of the white and black shrimps have DHA-to- EPA ratios of 1.05 and 2.15, respectively (Sriket and others 2007). The farmed freshwater prawn (*M. rosenbergii*) and the wild marine shrimp species (*Paracoccidioides brasiliensis, Penaeus schimitti,* and *Xiphopenaeus kroyeri*) have about 1% lipids. The principal fatty acids in the marine shrimp were C16:0, C16:1n-7, C18:0, C18:1n-7, C18:1n-9, C20:4n-6, C20:5n-3, and C22:6n-3. The major fatty acids in the freshwater prawn were C16:0, C17:0, C18:0, C18:1n-7, C18:1n-9, C18:2n-6, C20:5n-3, and C22:6n-3. The data suggested differences in fatty acid profiles of freshwater and marine species (Bragagnolo and Rodriguez-Amaya 2001).

Lipid profiles of cephalopods have been examined in detail. The mantles of the cephalopods *E. moschata* and *S. officinalis,* and *Todarodes sagittatus* have about 2% crude lipid contents; neutral lipids are 25% to 50% of total lipids. The fatty acids are rich in EPA and DHA (Sinanogluu and Meimaroglou 1998). Ozogul and others (2008) reported that the common cuttlefish (*S. officinalis*), European squid (*L. vulgaris*), common octopus (*O. vulgaris*), and musky octopus (*E. moschata*) had PUFA, SFA, and MUFA contents of 43.6% to 56.5%, 28.2% to 35.3%, and 4.4% to 9.5%, respectively. The highest proportions of SFA in cephalopods were myristic acid (C14:0, about 1% to 3%), palmitic acid (C16:0, 15.5% to 25.2%), heptadecanoic acid (C17:0, 1.1% to 2.6%), and stearic acid (C18:0, 4.3% to 10.0%). MUFA was composed of oleic acid (*cis*18:1*n*-9, 1.8% to 4.3%) and *cis*-11-eicosenoic acid (C20:1, 2.1% to 4.7%). PUFA consisted of arachidonic acid (C20:4 *n*−6, 1.5% to 11.7%), EPA, 7.9% to 17.0%, and DHA, 21.0% to 39.0%. There was also about 2% linoleic acid (C18:2 *n*-6) (Ozogul and others 2008). The fatty acids of the common octopus (*O. vulgaris*) consisted of 58.6% of n-3 PUFA (composed of 20.1% EPA and 26.3% DHA), 25.9% SFA, and 15.4% MUFA (Vaz-Pires and others 2004). The contents of n-3 PUFA in the squids *Loligo pealei* and *Illex illecebrosus* were above 50% of total fatty acids (Krzynowek and others 1989). In the cuttlefish (*S. lycidas*), PUFA was about 45% of total fatty acids. DHA was the dominant n-3 PUFA. The ratio of n-3 to n-6 PUFA was 2.48 (Wen and others 2015).

The mussel (*M. coruscus*) has higher contents of PUFA than SFA and MUFA; with DHA and EPA comprised 12% to 18% and 10.8% to 14.6% of total fatty acids, respectively (Li and others 2010a). Snail tissues contain significant amounts of both n-3 and n-6 PUFA. The contents of n-3 PUFA and SFA in the marine snail meat were about 68% and 33% of the total fatty acids, respectively. Comparable values were also found in snail hepatopancreas (Zarai and others 2011). The PUFA of Asian hard clam contained 46% to 49% of total fatty acids, with 13% to 16% DHA, and 5% to 7% EPA (Karnjanapratum and others 2013). The raw hepatopancreas of green crab (*C. mediterraneus*) has about 23% lipids; its claw meat had about 1% lipids only. The main SFAs were palmitic and stearic acids. Palmitic acid represented 11.5% to 12.4%, and 11% to 11.5% of the total fatty acids in the hepatopancreas and law meat, respectively. The contents of stearic acid were 7.8% to 8.3% and 7.0% to 7.3% in the hepatopancreas and in the claw meat, respectively. Oleic acid was the dominant MUFA, which represented up to 15.0% to 17.7% of the fatty acids in hepatopancreas. Arachidonic acid (20:4n-6) formed 13.5% of total fatty acids in the tissues (Cherif and others 2008). The total fatty acids of green crab (*Carcinus maenas*) had 20.7% SFA and 40.0% PUFA; the latter was dominated by EPA and DHA, with the ratio of EPA-to-DHA ranging from 1.6 to 2.8 (Naczk and others 2004). The PUFA contents of 2 abalone species (*Haliotis* spp.) accounted for over 40% of total fatty acids. The major fatty acids identified in muscle and viscera were C16:0, C18:0, C20:4n-6, C20:5n-3, and C22:5n-3 (Lou and others 2013). Krill oil contained 27% PUFA, 20% to 33% phospholipids, and 64% to 77% nonpolar lipids (Tou and others 2007).

Cholesterol and other sterols

Cholesterol is the main sterol present in shellfish, while other sterols such as stigmasterol, desmosterol, stigmasterol, C-26 sterol, and sitosterol may also be present in low amounts (Dong 2001). Cholesterol content is independent of fat content and is comparable in wild and cultivated samples (Kanazawa 2001). Table 1 (Source A, column IV) gives cholesterol contents of some shellfish. Raw shellfish including mollusks contained cholesterol up to 19 mg% in muscle tissue (Ozogul and others 2015). Crustaceans, bivalves, and cephalopods may contain total sterols at 150 to 250 mg%, w. wt. (NMFS 1987; Dong 2001; Turan and others 2011). Hard clam had 70 to 210 mg% cholesterol, w. wt. (Karnjanapratum and others 2013). During summer, the red shrimp and pink shrimp contained cholesterol at 60.8 and 57.8 mg%, w. wt., respectively (Rosa and Nunes 2004). Cholesterol contents of in raw meat of squids (*L. pealei* and *I. illecebrosus*) over a 2-y period ranged about 110 to 450 mg% (Krzynowek and others 1989). Cholesterol levels (mg/100 g) in the raw meat of shellfish from Indian markets were: cuttlefish, 130 to 162; squid, 188 to 198; Antarctic krill, 33.7 to 103; prawn, 118 to 169; crab, 54 to 67; lobster, 220; and oyster, 160 (Mathew and others 1999). The sterol ranged from 114 mg% in the wild shrimp *P. brasiliensis* to 139 mg% in the farmed freshwater prawn *M. rosenbergii* (Bragagnolo and Rodriguez-Amaya 2001).

Carbohydrates

The contents of carbohydrate including dietary fiber in shellfish tissue are low. Carbohydrate varies from 1.3% in cooked lobster meat to 2% to 3% in oyster, and the green mussel (USDA 2012; FAO/INFOODS 2016). Glycogen contents of 1.0% to 1.2% were recorded during winter in red shrimp, pink shrimp, and Norway lobster (Rosa and Nunes 2004). Pacific oyster had a glycogen content of 6.5 ± 3.0%, d. wt., during winter (Dridi and others 2007). Asian hard clam had a maximum of 7.9% carbohydrates (Karnjanapratum and others 2013) The mussels (*Mytilus* spp.) contained mytilan, a noncovalently linked complex of 95% polysaccharide and 5% protein, and another polysaccharide, a (1-4)-ᴅ-glucan (Grienke and others 2014).

Carotenoids

Carotenoids influence color of shellfish including processed items and hence affect their consumer acceptability. Animals, including humans, do not synthesize carotenoids *de novo* and rely upon diet as the source of these compounds. Shellfish accumulate carotenoids in their body tissues from carotenoid-rich marine plants, which are used as their feeds. The carotenoids can be either hydrocarbons or xanthophylls (the oxygenated derivatives), and include astacene, astaxanthin, canthaxanthin, cryptoxanthin, fucoxanthin, lutein, neoxanthin, violaxanthin, zeaxanthin, alloxanthin, and β-carotene (Shahidi and others 1998; Venugopal 2009; de Carvalho and Caramujo 2017). The carotenoids, β carotene and β cryptoxanthin, ingested by the animals may be converted to different compounds including vitamin A. Carotenoid contents vary depending on body parts of shellfish; they are high in their carapace, followed by head; while their meat has minimum contents. For example, the total carotenoid contents (mg/g) of raw meat, head, and carapace of shallow water shrimp (*P. monodon*) are 17.4, 58.4, and 86.6, respectively. The carotenoid contents (mg/g) of raw meat, head, and carapace of some other shellfish species are: shallow water shrimps (*Metapenaeus dobsoni*), 11, 51, and 83; *Parapeneopsis stylifera*, 16, 153, and 104; *P. indicus*, 10, 36, and 60; deep sea shrimps, *Solonocera indica*, 15, 68, and 116; and *Arcotheres alcocki*, 21, 185, and 117, respectively (Soumya and Sachindra 2015). The carotenoid content in raw body tissues of scallop ranged from 7 to 60 μg/g. The pigment contents varied in this order: gonad > mantle > adductor > gill (Zheng and others 2010).

Astaxanthin is the red-orange-colored carotenoid, which remains either free or bound to macromolecules such as proteins and/or chitin, in shrimp, prawn, krill, crab, and lobster. The pigment is formed from β-carotene or zeaxanthin through oxidative transformation (Soumya and Sachindra 2015). Astaxanthin is the major carotenoid present in the meat and shell of Indian shrimp (Sachindra and others 2005a) and marine and freshwater crabs (Sachindra and others 2005b). Other shellfish carotenoids include canthaxanthin present in crayfish, mytiloxanthin in mussel, and mactraxanthin and fcoxanthinol present in clams (Sachindra and others 2005a, 2005b; Grienke and others 2014). Balachandran (1976) reported the presence of lutein and astacene, in addition to astaxanthin, in Indian prawn (*P. stylifera*). The main pigment in the muscle tissues of the Yesso scallop, one of the important farmed scallops in China, was identified as pectenolone (3, 3′-dihydroxy-β, β-caroten-4-one) (Li and others 2010b).

Vitamins

Shellfish species contain most of the vitamins, particularly vitamin B_{12}. Typical contents are shown in Table 3. The vitamin contents may vary significantly in crustaceans. Oyster, blue mussel, and clam tissues are good sources of niacin and vitamin B_{12}. Contents of vitamin B_{12} are generally higher in muscle tissues of crab and lobster (FAO/INFOODS 2016). Shrimp, blue mussel, oyster, and scallop are good sources of vitamin A (NMFS 1987; Venugopal and Shahidi 1996; Souci and others 2008; USDA 2012). Shrimp recorded vitamin D_3 content of about 0.06 μg/100 g (Bogard and others 2015).

Minerals

Raw shellfish species have ash contents up to 2.0%, as shown in Table 2. Shellfish minerals contain both macroelements, (sodium [Na], potassium [K], calcium [Ca], phosphate [Pi],and magnesium [Mg]), and microelements (chromium [Cr], cobalt [Co], copper [Cu], fluorine [F], bromine [Br] iodine [I], iron [Fe], selenium [Se], zinc [Zn], and manganese [Mn]) (Anthony and others 1983; NMFS 1987; Dong 2001; Souci and others 2008; USDA 2012). As shown in Table 4, most shellfish are good sources of Na, K, Pi, Fe, Zn, Se, and Cu. Indian shrimp has Na, K, Ca, Mg, and Pi at 107, 58, 303, 250, and 176 mg/100 g raw edible meat, respectively (Gopakumar 1997). Mollusks and crustaceans contain appreciable levels of Cu and Zn (Dong 2001). Oysters are rich in zinc, iron, and copper (Venugopal and Shahidi 1996). Recent studies have examined mineral contents of shellfish. Mg was the dominant mineral in white and black shrimps, followed by Ca and Fe (Sriket and others 2007). The blue crab has significant contents of Ca, Mg, Pi, and Na, and their contents vary in claw, breast meat, and hepatopancreas of the crab (Küçükgülmez and others 2006). The edible portions of clam are rich in Na, K, Ca, Mg, Fe, Zn, and Cu (Karnjanapratum and others 2013). The meat and hepatopancreas of snail are rich in proteins and EAAs (Zarai and others 2011). The contents (mg/100 g) of iron, zinc, and calcium in 55 samples of fresh fishery products including shrimp from Bangladesh ranged from 0.34 to 19, 0.6 to 4.7, and 8.6 to 1000, respectively. Shrimp had maximum copper and iodine contents of 1200 and 120 μg/100 g, respectively (Bogard and others 2015). Fresh shellfish contain iodine at values ranging from 308 to 1300 μg/kg (FAO/WHO 2004; Oehlenschläger 2012). Shrimp shell has more iodine and bromine than raw or cooked tissues (Mesko and others 2016).

Factors influencing proximate composition

Habitats, season, feed, species, and life cycle. Habitats, season, feed, species, and also gametogenesis and spawning cycle can influence proximate composition of shellfish species (Berge and Barnathan 2005; Ozogul and others 2008; Li and others 2010a, 2011). Marine shrimp have much higher total n-3 PUFA than n-6 PUFA, while most of the freshwater shrimp demonstrated much lower total n-3 PUFA than n-6 PUFA (Li and others 2011). Bragagnolo and Rodriguez-Amaya (2001) found that the fatty acid compositions of marine shrimp (*P. brasiliensis*) and the popular farmed freshwater prawn (*M. rosenbergii*) were different, although both species contained total lipids of about 1.0%. Yerlikaya and others (2013) reported that fatty acid profiles of different shrimp species caught from deep water and shallow water varied. The main fatty acids were C18:1n9, C16:0, C25:6n3, C22:5n3, and C18:0. Saturated, monounsaturated, and PUFA contents of deep water shrimp, *P. longirostris* and *Porcellanopagurus edwardsi*, and shallow water shrimp, *Metapenaeus monoceros*, were markedly different. The shallow-water shrimp species may contain higher levels of PUFA than their deep water counterparts, presumably due to higher contents of PUFA-rich phytoplankton at the surface. Harvesting areas can influence color and lightness value of Mediterranean giant red shrimp; carotenoids in the crustacean varied with habitats (Bono and others 2012). Mineral compositions of mollusks depend on their living environments (FAO/INFOODS 2016). Proximate composition and mineral contents of thick shell mussel varied seasonally except for calcium and lead (Li and others 2010a). Iodine and selenium contents tend to be largely dependent on environmental conditions (FAO/WHO 2004). The proximate composition of 55 fishery products, including shrimp and prawn from capture (marine and inland) and aquaculture sources, varied depending on their habitats and species (Bogard and others 2015).

Seasonal changes in shellfish composition have been reported. Su and others (2006) reported significantly higher levels of total lipids including the SFA in 2 abalone species in summer, while the contents of total n-3 and n-6 PUFAs and total MUFA were higher in winter and spring. The major PUFAs were EPA (34% to 43%), and docosapentaenoic acid (DPA) (40% to 53%). The contents of DPA were significantly higher in winter, spring, and summer than in autumn. A higher n-3/n-6 PUFA ratio was found in winter and autumn in green lip abalone (Su and others 2000). Pink and red shrimp displayed lower values for cholesterol in summer than winter (Rosa and Nunes 2004). Glycogen contents of shrimp and lobster varied during winter and summer, maximum glycogen occurring in oyster between December and February (Rosa and Nunes 2004). Proximate composition and mineral contents of the thick shell mussel (*M. coruscus*) vary with season. PUFA predominated over SFA and MUFA throughout the season. DHA (12.4% to 18.3%) and EPA (10.8% to 14.6%) were the major PUFA (Li and others 2010a). Higher levels of lipid and PUFA were found in Korean bivalve shellfish in early summer, with minimal values in late summer (Surh and others 2003). Proximate composition of the crab (*C. pagurus*) was affected by gender and season. During autumn, maximum yield of brown meat was recorded. Maximum contents of EAAs in muscle, taurine in all the tissues, EPA in male gonads, fat and cholesterol in the crab ovaries were recorded during autumn (Barrento and others 2009a).

Feed composition has been recognized to influence consumption and utilization of the feed, determining the sustainability of aquaculture (Jennings and others 2016). Shrimp fed with carotenoid-rich feed has improved color and hence better consumer acceptability (Parisenti and others 2011; de Carvalho and Caramujo 2017). The shrimp (*P. mondon*) fed with β-carotene-enriched feed resulted in accumulation of astaxanthin in its muscle, formed by the metabolic conversion of β-carotene. Besides improving the shellfish color, the dietary carotenoids reduced molting cycle, enhanced growth, and caused resistance to diseases,

Table 3–Vitamin contents of some shellfish meat.

Shellfish	A	B_1	B_2	B_6	B_{12}	E	K	Folic acid	Niacin
Shrimp[a]	2	51	34	130	2.0	–	–	12	–
Shrimp, mixed[b]	–	–	–	–	1.2	–	–	–	–
Shrimp mixed[c]	225 IU	–	0	0	1.5	1.4	0	4	2600
Shrimp[d]	189 IU	20	15	160	1.9	1.4	1	–	3070
Lobster[a]	–	130	88	1000	970	1500	0.1	12	–
Lobster, northern[c]	570 IU	0	100	100	3.1	1000	0.1	11	1100
Mussel[a]	54	160	220	76	8	750	–	16	–
Mussel, blue[b]	–	–	–	–	12	–	–	–	
Mussel blue[c]	304	300	400	100	24	–	–	76	3000
Cuttlefish[a]	3	70	30	0.4	–	1500	0.1	44	2300
Cuttlefish[c]	675 IU	–	1700	300	5.4	1500	0.2	24	2200
Cuttlefish[d]	375 IU		0.9	150	3	–		16	1216
Oyster[a]	93	160	160	200	15	850	100	7	–
Oyster, Pacific[b]		–	–	–	16	–	–	–	–
Oyster, eastern,		–	0.4	–	29	–	–	–	–
mixed[c]	180	200	200	100	35	–	–	–	2500
Clam, mixed[b]	–		–	–	49	–	–	–	–
Clam, mixed[c]	570 IU	200	400	3.4	100	–	–	29	3400
Scallop mixed[c]	100 IU	100	100	100	1.3		–	–	
Scallop mixed[d]	217 IU	70	15	73	1.5	0	–	–	703
Crab, blue[c]	7 IU	100	100	200	7.3	1800	0.1	51	3300
Crab, Alaska king[d]	24 IU	43	43	50	11.5	–	–	44	–
Crayfish[c]	50 IU	100	100	100	2.1	–	–	–	–
Cray fish mixed[d]	53 IU	70	32	08	2.1	–	–	44	2300
Squid, mixed species[d]	33 IU	20	400	56	1.3	1.2	–	5	2200

The values are in μg/100 g tissue. Some vitamin A values are given in international units, indicated as IU.
Sources: [a] Raw edible portions, Souci and others (2008).
[b] Raw edible portions, Dong (2001).
[c] Samples cooked under moist heat, SELFNutritionData.
[d] Cooked under moist heat, USDA (2012).
-, not reported.

thereby favoring increased shrimp production (Soumya and Sachindra 2015). Carotenoid contents of gonad and adductor muscle of female scallop are higher than those of male (Zheng and others 2010). The levels of tocopherols (α, β, γ, and δ) in cultured shellfish depend on the presence in their diets (Jennings and others 2016). Abundant availability of PUFA-rich phytoplankton in the surface waters can result in higher PUFA in lipids of shrimp (Yerlikaya and others 2013) and oyster (Dridi and others 2007; Chakraborty and others 2016b). The increase in the contents of total fatty acids during autumn correlated with availability of food rich in chlorophyll *a* concentrations (Yanar and Celix 2006). Proximate composition of European lobster (*Homarus gammarus*) and American lobster (*H. americanus*) differed with respect to body parts, sex, and species. Muscle and gonads were rich in protein, whereas hepatopancreas had high fat, cholesterol, and energy contents (Barrento and others 2009b). Gametogenic cycle has influence on biochemical composition of oyster (Dridi and others 2007).

Influence of processing

Chilled storage, freezing, cooking, steaming, and other treatments influence proximate compositions of shellfish species (USDA 2012; FAO/INFOODS 2016). PUFA can undergo oxidation during prolonged frozen storage, catalyzed by minerals such as copper and iron, present in the shellfish (Huss and others 2003; Venugopal 2006). Ice storage can result in an increase in moisture together with a decrease in total nitrogen content. Furthermore, there were changes in viscoelastic properties of the meat, suggesting denaturation of the proteins (Binsi and others 2007). Prolonged frozen storage may lead to protein denaturation and hence result in change of the moisture content of shrimp, with the water-to-protein ratio increasing from 5.5 to 7.5 (Saskia and Ruth 2014).

Heat treatments such as boiling and steaming, in general, have little impact on proximate composition of shellfish (Kreuzer 1984; Venugopal 2006; Su and Liu 2013). Cooking, in general, denatures muscle proteins and enhances their digestibility, and drastic heating can significantly reduce the protein quality (Venugopal 2006). Thermal stability of proteins differs depending upon the shellfish species. Muscle proteins from black tiger shrimp, especially myosin heavy chain, had higher thermal stability than those of white shrimp (Sriket and others 2007). Heating in the presence of oxygen, or sun drying, resulted in oxidation of PUFA associated with the formation of highly reactive peroxides, which react with proteins (Huss and others 2003). Cooking caused changes in composition, leaching of water and chitin-bound carotenoids from crab, enhancing the color of cooked meat (Maulvault and others 2012). Thermal processing of white shrimp (*L. vannamei*) resulted in up to 52% loss of astaxanthin depending on the treatment conditions. The trans-astaxanthin was reduced from 32.8 to 8.7 μg/kg during microwaving, drying, and frying, while 13-cis astaxanthin increased from 2.4 to 5.6 μg/kg. Astaxanthin diesters had higher thermal stability than monoesters of astaxanthin with either EPA or DHA (Yang and others 2015). During sun drying of cooked shrimp, up to 75% of astaxanthin was degraded along with a 6- to 8-fold increase in cholesterol oxidation products. Storage of the cooked product for 90 d resulted in up to 83% degradation of astaxanthin (Hernández Becerra and others 2014). Carotenoids bound to proteins are released by the action of digestive enzymes (Babu and others 2008). Cooking of shrimp resulted in up to 43% loss of iodine and bromine (Mesko and others 2016). Domestic pan-frying of squid and mussel in virgin olive oil caused up to 14% oil absorption together with an increase in squalene and MUFA contents (Kalogeropoulos and others 2004). Frying also caused significant loss in cholesterol and sitosterol contents (Ozogul and others 2015). Marination reduced the phospholipid content of soft

Table 4–Mineral contents of some shellfish meat.

Shellfish	Na	K	Mg	Ca	Pi	Fe	Zn	Se	Cu
Shrimp mixed[a]	146	230	67	92	224	6.1	2.2	0.1	0.9
Shrimp[b]	–	–	–	–	–	2.4	1.1	–	0.3
Tiger shrimp[c]	176	260	58.5	107	303	2.1	1.4	0.04	–
Shrimp, mixed[d]	546	170	37	70	237	0.5	1.6	–	–
Prawns (*P. borealis*), cooked[e]	–	–	–	–	–	–	–	0.03	0.02
Shrimp, mixed[f]	224	182	34	39	137	3.1	1.5	0.04	0.02
Lobster[a]	270	220	24	61	234	1.0	1.6	0.1	–
Lobster spiny, mixed[b]	–	–	51	63	–	1.2	5.7	–	0.4
Lobster, northern	486	230	43	96	185	0.3	4.1	–	–
Mussel[a]	296	–	30	24	200	4.2	1.8	0.1	–
Mussel, blue[b]	–	–	–	–	–	4.0	1.6	–	1.9
Mussel, *P. viridis*[e]	180	251	–	64	102	0.9	–	–	–
Mussel blue[f]	369	268	37	33	285	6.7	2.7	0.09	0.1
Cuttlefish, mixed[a]	387	273	–	27	143	8.0	0.7	0.07	–
Cuttlefish, *Sepia* spp.[e]	146	206	–	70	88	7.5	–	–	–
Cuttlefish[d]	744	637	60	180	580	11.0	3.5	–	–
Oyster[a]	160	184	32	82	157	3.3	22.0	0.03	–
Oyster, Pacific[b]	–	–	–	–	–	5.1	16.6	–	1.6
Scallop mixed[b]						0.3	1.0	–	0.05
Scallop, mixed[d]	667	304	37	6	426	0.6	1.5	–	–
Scallop, mixed[f]	74	133	15	32	95	0.6	0.8	0.01	0.1
Scallop, raw[g]	155	203	39	29	250	1.2	4.0	0.02	0.04
Clam, mixed[a]	–	–	–	–	–	14.0	1.4	–	0.3
Clam, *M. casta*[e]	81	130	–	76	106	0.9	–	–	–
Clam, mixed[f]	92	628	18	92	338	28	2.7	0.06	0.07
Squid, mixed[d]	44	246	33	32	221	0.7	1.6	–	1.9
Squid mixed raw[f]	12	70	9	9	62	0.2	0.4	0.01	0.5
Crab, blue[a]	–	–	–	–	–	0.7	3.5	–	0.1.
Crab, *S. serrata*[e]	186	378	–	68	150	1.0	10.2	0.05	1.6
Crab, Alaska king[d]	1072	262	63	59	280	0.8	5.9	–	7.6
Crab, Alaska king[f]	1435	351	–	79	375	–	–	–	–
Crayfish, mixed, cooked moist heat[d]	97	238	33	51	241	1.1	1.5	–	–

Values are given in mg/100 g or edible portions.
Sources: [a] Souci and others (2008).
[b] Dong (2001).
[c] Dayal and others (2013).
[d] USDA (2012) (cooked under moist heat).
[e] Department of Health, UK (2013).
[f] SELFNutritionData (samples cooked under moist heat, except squid).
[g] FSANZ (2011).
-, not reported.

clam with partial replacement of PUFA with MUFA (Papaioannou and others 2016). Thiamin is labile to heat, ionizing radiation, and low pH conditions. Riboflavin is reasonably stable to cooking, but is sensitive to light. Vitamin B_6 tends to get destroyed with prolonged cooking. Vitamin B_{12} is partially degraded and loses its biological activity during cooking and storage (Venugopal 2006).

Nutritive Value and Health Benefits of Shellfish

It is well recognized that adequate intake of nutrients is essential for good health. Several marine ingredients have been recognized to possess interesting bioactivities and hence health benefits (Abeynayake and Mendis 2014; Grienke and others 2014; Hamed and others 2015). This section discusses the nutritive value and health benefits of individual components of shellfish meat. An attempt is also made to quantify nutritive value in terms of recommended dietary intake values.

Proteins

Adequate intake of nutritious protein is crucial for health. The nutritive value of a protein is governed by its primary structure, amino acid composition, content of EAAs, susceptibility to enzymatic digestion, and extent of chemical changes due to processing such as thermal treatment (Friedman 1996). Animal feeding experiments are generally employed to determine nutritive values of proteins. These studies include the nitrogen balance method based on protein digestibility, determination of protein efficiency ratio (PER) (weight gained per gram of protein consumed), net protein utilization (ratio of amino acid converted to proteins to the ratio of amino acids intake), and biological value (a measure of absorption and utilization of protein by the living organism) (Friedman 1996). The protein digestibility corrected amino acid score (PDCAAS) is based on the amino acid content of food protein, its digestibility, and ability to supply EAAs according to requirement (Dong 2001). The PDCAAS of shrimp is 1, indicating its good protein quality (Dayal and other 2013). Seafood is an excellent source of proteins and contains all the EAAs. The proteins are easily digested; most proteins show a digestibility above 90% (Oehlenschläger 2012; Hamed and others 2015). Shellfish proteins have PER values that are slightly above that of casein, the major milk protein (Venugopal 2006). Krill concentrate has approximately 78% protein, which has a PER value equal to that of casein (Gigliotti and others 2008). The common octopus (*O. vulgaris*) has a biological value of about 84 (Kreuzer 1984). Amino acid score (AAS) of a protein is indicative of its nutritional quality, an AAS score of 100 means high protein quality (SELFNutritionData). As shown in Table 1, proteins of shellfish species, cooked under moist heat, have AAS scores as high as 100. The cuttlefish (*S. lycidas*) has AASs above 100 for all the amino acids, except for valine (93), while the EAA, tryptophan, has a value of 327 (Wen and others 2015). Shellfish proteins provide all the EAAs for maintenance and growth of the human body (Friedman 1996). Compared with suggested amino acid requirements by the FAO/WHO, the hydrolysates of the little loligo squid (*Uroteuthis chinensis*) has high nutritional value, and is a potential nutritious supplement used in various food products (Wu and others 2015). Shellfish and other seafood are good sources of branched chain amino acids and taurine, which act beneficially on glucose metabolism and also blood pressure (Elmadfa and Meyer 2017). Fermented shellfish sauces are nutritional condiments, which find uses in cuisines in African and south east Asian areas (Grienke and others 2014). In view of the high nutritional value, shellfish proteins are able to enhance the nutritive value of plant proteins, which may be deficient in 1 or more EAAs (Kim and Venkatesan 2015; Elmadfa and Meyer 2017).

Enzymatic digestion of proteins, either *in vitro* or in the human digestive system, leads to formation of several peptides besides amino acids. The digested protein can be absorbed in the intestine in the form of single amino acids, di- or tripeptides, and oligopeptides (Vijaykrishnaraj and Prabhasankar 2015). Bioactive peptides are protein fragments, which have attracted recent attention due to their interesting physiological functions. These include their antimicrobial, antiviral, antitumor, antioxidative, cardioprotective, immune-modulatory, analgesic, antidiabetic, antiaging, appetite-suppressing, and neuroprotective activities (Harnedy and FitzGerald 2012; Ngo and others 2012; Abeynayake and Mendis 2014; Cheung and others 2015). Angiotensin-I-converting enzyme (ACE) (EC3.4.15.1) plays crucial role in the regulation of blood pressure. The enzyme promotes conversion of angiotensin-I to the potent vasoconstrictor angiotensin II. Inhibition of ACE is considered a therapeutic approach in the treatment of hypertension. Several shellfish-derived peptides have been recognized to possess ACE-inhibitory activity (Harnedy and FitzGerald 2012; Cheung and others 2015). Clam peptides have ACE-inhibitory and hypocholesterolemic activities, bile acid-binding capacities, and the ability to inhibit solubility of cholesterol, indicative of their cardioprotective role (Lin and others 2010). Peptides having antioxidant, anticoagulant, and antihypertensive properties have also been isolated from mussel (Grienke and others 2014). A novel anticancer peptide from the shellfish *C. gigas* exhibited cytotoxic activity, inducing death of prostate, breast, and lung cancer cells (Cheung and others 2013). Antimicrobial activities are described in the hemolymph of spider crab, oyster, American lobster, shrimp, and green sea urchin (Cheung and others 2015). Indian shrimp is a source of a crustin-like putative antimicrobial peptide (Antony and others 2010), and also an antioxidant peptide (Gunasekaran and others 2015). Table 5 gives shellfish-derived peptides and their physiological functions. In addition to antioxidant peptides, amino acids such as phenyl alanine, histidine, and tryptophan in fish peptides may scavenge reactive oxygen species (ROS) such as hydroxyl radical (Dean and others 1997).

Lipids

As discussed earlier, shellfish are rich in n-3 PUFA, with a ratio of n-3 to n-6 PUFA above 1.0 (Passi and others 2002; Sriket and others 2007). Consumption of n-3 PUFA rich shellfish increases the ratio of n-3 to n-6 fatty acids in the body. The n-3 PUFA are rich in EPA and DHA. Both EPA and DHA are known to play important roles in growth, development, and maintenance of health (Gogus and Smith 2010; Hossain and Takahashi 2012). The mode of action of the PUFAs is attributed to their ability to give rise to a class of pharmacologically important groups of compounds, such as prostaglandins, prostacyclins, thromboxanes, and leukotrienes (collectively called eicosanoids). Both n-3 and n-6 PUFA are precursors of eicosanoids. Eicosanoids derived from n-6 PUFA, such as arachidonic acid, have pro-inflammatory functions, whereas eicosanoids derived from n-3 PUFA have anti-inflammatory properties (Calder 2014). The n-3 PUFA-derived eicosanoids antagonize the formation of inflammatory prostaglandin E_2, derived from arachidonic acid and other n-6 PUFA. The n-3 PUFAs impart their anti-inflammatory effects via reduction of nuclear factor-κB activation. This transcription factor is a potent inducer of pro-inflammatory cytokine production. Besides, both EPA and DHA are also able to increase secretion of adiponectin, an anti-inflammatory adipokine (Siriwardhana and others 2012). Through these actions, the n-3 PUFA alter cell and tissue functions that favor disease prevention and maintenance of health (Calder 2014).

There is strong evidence to suggest protective effect of n-3 PUFA including EPA and DHA on the risk of cardiovascular disease and stroke (Kris-Etherton and others 2002; Weichselbaum and others 2013; Hamed and others 2015). Intake of n-3 fatty acids has also shown to lower serum cholesterol, which is beneficial to cardiac health (Gogus and Smith 2010). A global study comprising 16 countries, 45637 individuals, 7973 cases of coronary heart diseases (CHDs), 2781 fatal CHDs, and 7157 nonfatal myocardial infarction events suggested that long-chain n-3 PUFA are associated with modestly lower incidence of fatal CHD (Gobbo and others 2016). Other studies also indicate that long-chain n-3 PUFA can have anticancer, antidepression, antiaging, and antiarthritis effects. They can also address a number of chronic diseases, including a spectrum of liver fat-related conditions and kidney functions (Cardoso and others 2010; Wall and others 2010; Scorletti and Byrne 2013; Calder 2014). DHA is crucial for development of the brain and the central nervous system in infants and to suppress neuroinflammation and oxidative stress (Abeynayake and Mendis 2014). In view of their recognized health benefits, professional bodies such as American Heart Assn., Dept. of Health, U.K. Food Standards Agency (FSA), among others, suggest daily total intake of EPA and DHA varying from 250 to 1000 mg/d (Venugopal 2009; Hellberg and others 2012; Weichselbaum and others 2013). Interests in these fatty acids as food supplements have attracted a current global market valued at U.S.$3.9 billion for these compounds (GOED 2017).

Carotenoids

In food items, reactive oxygen species (ROS) are formed enzymatically, chemically, and photochemically. Autooxidation of unsaturated lipids leads to formation of peroxy radicals ($ROO^{\cdot}$). Other ROS include superoxide anion ($O_{2.}^{-}$), hydroxyl radical ($HO_{.}^{-}$), and alkoxy radical ($RO_{.}^{-}$), among others. Nonradical derivatives are hydrogen peroxide (H_2O_2), ozone (O_3) and singlet oxygen ($^1O_2$). The hydroxyl radical is the most reactive ROS, followed by singlet oxygen. Reactions of ROS with food components destroy nutrients, change the functionalities of proteins, lipids, and carbohydrates, and lead to the formation of undesirable volatile compounds and carcinogens. Oxidative modifications of n-3 and n-6 PUFAs result in the formation lipid oxidation products, such as malonldehyde and others, which adversely react with food components resulting loss of their functional properties (Choe and Min 2006). Oxidation of low-density lipoproteins (LDLs), induced by oxidative stress (a situation arising when the balance between pro- and antioxidants is disturbed), plays a key role in inflammation and progression of atherosclerosis (Abeynayake and Mendis 2014).

Antioxidants are compounds that can inhibit or retard oxidation either by scavenging the free radicals that initiate oxidation or

Table 5–Shellfish-derived bioactive peptides and their physiological functions.

Shellfish	Sequence and other characteristics	Functions/activities
Shrimp (protease)	Le-Phe-Val-Pro-Ala-Phe	ACE inhibitory
Shrimp (cryotin)	Peptide[b] (molecular size, <10, 10 to 30, >30 kDa)	Anticancer
Wakame (papain)	Tyr-Asn-Lys-Leu	–
Oyster	Cys, Leu, Glu, Asp, Phe, Tyr, Ile, Gly	Antimicrobial
American lobster	Gln-Tyr-Gly-Asn-Leu-Leu-Ser-Leu-Leu-Asn-Gly-Tyr-Arg	Antimicrobial
Jumbo Squid	Gelatin peptide[a]	Antioxidant
Blue mussel (fermentation)	Glu-Ala-Asp-Ile-Asp-Gly-Asp-Gly-Gln-Val-Asn-Tyr-Glu-Glu-Phe-Val-Ala-Met-Met-Thr-Ser-Lys	ACE inhibitory, anticoagulant, antioxidant
Scallop	γ-Glutamyl-valyl-glycine	Flavoring agent
Spider crab	Proline-arginine-rich peptide[a]	Antimicrobial
Snow crab (protamex)	Cationic peptide[a]	Anticancer
Oyster	Peptide[a]	Anticancer, immune-stimulant
Clam (thermolysin)	Peptide[a]	ACE inhibitory
Clam (protamex)	Various peptides[a]	Hypocholesterolemic effect
Oyster (thermolysin)	Peptide[a]	Antioxidant, antihypertensive
Oyster (subtilisin)	Pro–Val-Met-Gly-Asp and Glu-His-Gly-Val peptides	Antioxidant
Squid skin collagen	Peptide[a]	ACE inhibitory
Krill	Various peptides[a]	ACE inhibitory
Naturally present peptides in raw muscle		
Crab, shrimp	Crustin or crustin-like, Callinectin, Tachyplesin	Antibacterial, antifungal, antiviral
Crayfish	Astacidin[a]	Antibacterial, antifungal, antiviral
Lobster	Crustin or crustin-like[a]	Antibacterial, antifungal, antiviral
Mussel (Neutrase)	Tyr-Pro-Pro-Ala-Lys	Antioxidant
Mussel	Mytilin, mytimycin, Myticin, Pernin[a]	Antibacterial, antifungal, antiviral
Shrimp	Penaeidin, crustin-like peptide	Antimicrobial, antifungal, antioxidant
Scallop	γ-Glutamyl-valyl-glycine	Flavoring agent

[a] Sequence of peptide not reported.
Proteases used for hydrolysis are given in parenthesis.
Sources: Summarized from Lin and others (2010); Antony and others (2010); Harnedy and FitzGerald (2012); Wang and others (2013); Cheung and others (2013); Cheung and others (2015); Gunasekaran and others (2015); and Vijaykrishnaraj and Prabhasankar (2015).

by breaking the oxidative chain reactions. Carotenoids are dietary antioxidants (in addition to tocopherols, vitamin C, and polyphenols including flavonoids). The antioxidant activities of carotenoids have been attributed to the presence of conjugated double bonds in their structures (Lordan and others 2011; Chuyen and Eun 2017). Carotenoids are able to quench singlet oxygen and act as *in vivo* scavengers of ROS. The singlet oxygen scavenging ability is the highest for β-carotene, followed by tocopherol, riboflavin, vitamin D, and ascorbic acid (Choe and Min 2006). Furthermore, carotenoids, in general, possess anti-inflammatory properties, presumably due to their effects on intracellular signaling cascades, thereby inhibiting production of inflammatory cytokines (Kaulman and Bohn 2014).

Astaxanthin, the major shellfish carotenoid, has the ability to protect body tissues from oxidative damage by UV-light. It also has anti-inflammatory and cardioprotective properties. The antioxidant activity of astaxanthin is higher than that of β-carotene, lutein, lycopene, α-tocopherol, and canthaxanthin. Other potential health benefits of astaxanthin include its anticancer, antiaging, and immunostimulating activities. The carotenoid also possesses antidiabetes properties, controls cataracts, and inactivates Gram-negative bacteria also *Helicobacter pylori,* responsible for chronic gastritis (Hussein and others 2005; Higuera-Ciapara and others 2006; de Carvalho and Caramujo 2017). Canthaxanthin and β-carotene protect macrophage receptors from ROS, while β-carotene protects neutrophils, a major class of white blood cells, which use ROS to kill phagocytized bacteria (Abeynayak and Mendis 2014).

Vitamins and minerals

Shellfish vitamins serve interesting physiological roles Vitamin A has a wide variety of functions, including specific roles in vision embriogenesis, cellular differentiation, growth, reproduction, immune status, and taste sensations. Vitamin D deficiency leads to impaired mineralization of bone due to an inefficient absorption of dietary calcium and phosphorus, and is associated with an increase in parathyroid hormone serum concentration (Wardlaw and Smith 2009). Vitamin B_{12} (cobalamin) deficiency may cause health disorders such as megaloblastic anemia and neuropsychiatric disorders (Hamed and others 2015). The tocopherols are powerful antioxidants (Alfonso and others 2016). Iodine available from shellfish is a key constituent of thyroid hormones (Institute of Medicine, IOM 2007; Wardlaw and Smith 2009; James 2013).

The physiological roles of minerals present in shellfish have been reported (Seafish 2017). Copper is a part of certain enzymes that are required to prevent oxidative damage of cell membranes and also regulate neurotransmitters. Iron is part of hemoglobin present in red blood cells and is involved in oxygen transport. Calcium can function as a pro-oxidant. Zinc helps in immune functions, healing of wounds, development of bones, and the cell membrane structure and functions. Zinc also may have a protective effect against atherosclerosis because of its anti-inflammatory and antioxidant functions (Bao and others 2010, Nesheim and Yaktine 2010). Selenium is essential for normal physiology, particularly that of the brain and endocrine tissues (Finley 2007). In humans, 25 proteins containing the amino acids, seleno-cysteine and/or seleno-methionine have been identified. These include the glutathione family of enzymes having antioxidant functions, and the thioredoxin reductase family, involved in cellular respiration (Rayman 2000). The positive role of selenium in countering prostate and colorectal cancers has also been indicated (Seafish 2017). Furthermore, selenium and its derivatives are able to protect against mercury intoxication (Bjerregaard and Christensen 2012; Khora 2014). Olmedo and others (2013) observed that most shellfish have beneficial Hg to Se ratios and Se-health benefit values.

Shellfish are low in calories due to their low lipid and carbohydrate contents (Nettleton and Exler 1992; Dong 2001). Cooked 100 g portions of blue crab, clam, oyster, scallop, or shrimp provide 95 to 160 kcal only (Food and Drug Administration, FDA 2008). Cooked warm water prawn (*Pandalus borealis*) has a calorie content of 68 kcal (295 kJ)/100 g, while the cold water prawn (*P. vannamei*) has a slightly higher calorie content than *P. borealis* (Department of Health, UK 2013). The values for cooked brown, and white crab meats are 145 kcal (608 kJ), and 85 kcal (360 kJ)/100 g, respectively (UK FSA 2017).

Determination of nutritive value of shellfish meat components

Dietary guidelines are the key recommendations to the general population on requirements of adequate nutrients within caloric needs, necessary for maintenance of health, weight management, and physical activity. The U.S. 2015 to 2020 *Dietary Guidelines* provides consumers of different age and sex guidance to choose a healthy eating pattern to prevent diet-related chronic diseases. The *Guidelines* are designed to meet the Recommended Dietary Allowances (RDAs), and the Adequate Intakes for Essential Nutrients set by the IOM (Anonymous 2015). The *Guidelines* recommend daily intake of the following amounts of nutrients by males aged 19 to 30, namely: protein, 56 g; total fat, 20 to 35 g (saturated fat, <10% of total fat); macrominerals (in milligrams; Na, 2300; Ca, 1000; K, 4700; Pi, 700; and Mg, 400); microminerals (in milligrams except vitamin D and vitamin B_{12}; Fe, 18; Zn, 11; Mn, 2.3; Cu, 0.9; and Se, 0.055); vitamins (in milligrams; A, 900; B_1, 1.2; B_2, 1.3; B_6, 1.3; B_{12}, 2.4 μg; niacin, 16; D, 600 IU; E, 15; K, 0.1, and folate 400); vitamin D, 800 IU; and calories 2400 to 3000. The daily nutritional goals for other age and sex groups are also given in the Guidelines (Anonymous 2015).

The RDA values can be used to determine the nutritive value of shellfish meat in terms of Percent Daily Value (%DV) of individual nutrients. For example, against the requirement of 56 g for protein by a male adult, as mentioned earlier, consumption of 100 g cooked shrimp meat containing 23.5 g protein fulfils 42% of his daily protein requirement. Therefore, "42" is the %DV for protein in shrimp. Table 6 gives the %DV for nutrients present in meat of various shellfish types, cooked under moist heat. It can be seen that most shellfish have %DV values of about 50 for proteins. Dayal and others (2013) calculated %DV for various nutrients present in tiger shrimp (*P. monodon*). They reported %DV values of 75 for total EPA and DHA contents, and a value of 70 for the EAAs methionine, tryptophan, and lysine present in the shellfish. Selenium has a %DV as high as 110, suggesting the shrimp fully satisfied the dietary requirement for this mineral (Dayal and others 2013). A 100-g serving of shellfish, except squid, scallop, and crayfish can provide appreciable amounts of the vitamin B_{12} necessary to satisfy its dietary requirement, as shown in Table 6. Most shellfish species also provide significant amounts of selenium and also copper, as shown by their %DV values (Table 6). In a recent study, potential contributions of nutrients from 55 species of shrimp, and prawn (and also finfish), from diverse habitats to satisfy public health requirements, were determined. Seven species, including prawn could simultaneously satisfy ≥25% of recommended nutrient intakes for 3 or more nutrients. Iodine from shrimp and prawn satisfied more than 25% of its nutritional requirement (Bogard and others 2015). It has been recognized that the nutritional impact of shellfish consumption may be greater than the sum of the health benefits from individual nutrients (FAO/WHO 2011).

The nutritive values of various shellfish species have been pointed out in detail by various compositional studies. Although these studies do not attempt to quantify the nutrient contents in terms of %DV, they do point out nutritional values with respect to shellfish species. A few examples are cited. The giant red shrimp, as well as Norway lobster, are valuable sources of nutrients, including proteins, antioxidants, among others, for the human diet (Rosa and Nunes 2004). The muscle and gonads of female crab (*C. pagurus*) has favorable n-3 to n-6 ratios, and a well-balanced EAA composition (Barrento and others 2009a; Maulvault and others 2012). American and European lobsters have nutritive values compatible with nutritional foods (Barrento and others 2009b). The mussel *P. viridis* has balanced ratios of essential to non-EAAs, and also of *n*-3 to *n*-6 PUFA contents (Chakraborty and others 2016a). Furthermore, the consumption of mollusks can make an important contribution to the daily dietary intake requirement of Se, Cu, and Zn (Storelli and others 2010). Shellfish and other seafood provide good measures of vitamin B_{12} and vitamin D (Anonymous 2015). The presence of appreciable levels of PUFA (including EPA and DHA), vitamins, minerals, and amino acids qualifies the oyster (*Crassostrea madrasensis*) a potential "health" food. The shellfish has also atherogenic and thrombogenicity indices together with a good hypocholesterolemic to hypercholesterolemic ratio, pointing out its health benefits (Chakraborty and others 2016b). The blue crab could be used as a dietary supplement to balance human nutrition (Küçükgülmez and others 2006). Nutritional claims have also been made with respect to common octopus (Vaz-Pires and others 2004) and Asian hard clam (Karnjanapratum and others 2013).

Nutritive value of farm-raised shellfish

Farmed shellfish can have as high levels of nutrients as their wild counterparts (Nettleton and Exler 1992; Bragagnolo and Rodriguez-Amaya 2001). Cultivated thick-shell mussels represent a source of health-benefiting long-chain *n*-3 PUFA, EAAs, and minerals (Li and others 2010a). Abalones farmed in China have abundant n-3 PUFAs, particularly EPA (Su and others 2000; Lou and others 2013; Suleria and others 2017). The popular farmed marine mussels belonging to *Mytilus* spp. and *Perna* spp. provide good levels of proteins, EAAs, n-3 PUFAs, and minerals (Li and others 2010a; Grienke and others 2014). As feeds are known to influence proximate composition, as pointed out earlier, the potential exists to enhance the nutritive value of farmed shellfish using nutrient-enriched feeds. Microalgae-supplemented feed has been shown to increase the PUFA contents in clams, oysters, and scallops (Berge and Barnathan 2005). Feeding scallops with spirulina, the brown green microalga, known to be rich in carotenoids and n-3 PUFA, helps the development of the shellfish gonads, resulting in higher fecundity, hatchery rate, and also possibly increased contents of n-3 PUFA in the shellfish (Zhou and others 1991).

Seafood, which includes shellfish and finfish, received particular attention in the *2015 U.S. Dietary Guidelines,* which observed evidence of health benefits for the general population, as well as for women who are pregnant or breastfeeding. For the general population, consumption of about 8 oz/wk consisting of a variety of seafood, which will provide an average consumption of 250 mg/d of EPA and DHA, is associated with reduced cardiac deaths among individuals. Consumption of DHA-rich seafood is associated with improved infant health outcomes (Anonymous 2015).

Shellfish-derived nutraceuticals

Nutraceuticals are defined as substances that may be considered part of a food that provide health benefits, including the prevention and treatment of disease(s) (Venugopal 2009). Shellfish constituents such as carotenoids, PUFAs, bioactive peptides, among others

Table 6–Percent daily values (%DV) for protein, some vitamins, and minerals from shellfish.

		Vitamins				Minerals						
Shellfish	Protein	A	B_1	B_2	B_{12}	Fe	K	Se	Cu	Zn	Mn	Pi
Shrimp, mixed species	42	–	–	–	25	17		57	10	10	2	17
Tiger shrimp[a]	54	4	–	–	–	14		110	68	12	2	51
Shrimp[b]	4	0				10	6					
Oyster, mixed species	36	–	–	11	584	67	–	102	378	1211	35	20
Oyster[b]	26	–	–	–	–	45	6	–	–	–	–	–
Squid, mixed species	–	1	1	24	22	4	–	64	95	10	2	7
Mussel, blue	48	6	20	25	400	37	–	125	7	18	340	28
Lobster, mixed species	51	2	0	4	52	2	–	61	97	19	3	19
Lobster[b]	54	–	–	–	–	2	9	–	–	–	–	–
Crab, blue	40	0	7	3	122	–		57	32	26	9	21
Crab, Alaska king	39	1	4	3	192	4	–	57	59	51	2	28
Blue crab[b]	52	–	–	–	–	4	9	–	–	–	–	–
Scallop, bay	40	2	7	4	22	17	–	40	15	20	–	34
Scallop[b]	58	–	–	–	–	4	12	–	–	–	–	–
Clam, mixed species	51	11	10	25	1648	155	–	91	34	18	50	34
Clam[b]	44	–	–	–	–	30	13	–	–	–	–	–
Crayfish, mixed, farmed	35	1	3	4	30	4	–	52	34	12	26	24
Cuttlefish	65	13	1	102	90	60	–	128	50	23	10	58

The values are given for 100 g shellfish cooked under moist heat.
Sources: SELFNutritionData; [a] Dayal and others (2013); [b] FDA (2008).
-, not reported.

can be valuable nutraceuticals for the development of functional foods, defined as foods with specific beneficial health effect beyond simple nutrition (Hasler 1998; Venugopal and Lele 2014). Crustacean polysaccharides, particularly chitin and its derivatives, have pharmaceutical properties such as antioxidant, anti-inflammatory, antiallergic, antitumor, antiobesity, antidiabetes, anticoagulant, antiviral, immunomodulatory, cardioprotective, and antihepatopathy activities, which offer potential applications as bioactive food ingredients as well as nutraceuticals (Vo and others 2015). The mussel polysaccharide mytilan possesses antibacterial, antioxidant, and immune-modulating activities. In addition, another polysaccharide, a (1-4)-D-glucan, present in mussel is known to exhibit antioxidant activity and a protective effect on acute liver injury in mice (Grienke and others 2014). A lipid extract of hard-shelled mussel (*M. coruscus*) possesses strong anti-inflammatory activity and has the potential to treat rheumatoid arthritis (Fu and others 2015). The immune-strengthening properties of New Zealand green lipped mussel extract are valuable to relieve osteoarthritis, joint pain, and also atopic asthma (Emelyanov and others 2002). The high oxyradical scavenging capacity and total phenolics suggest the nutraceutical potential of the mussel *P. viridis* (Chakraborty and others 2016a). Abalone is a source of valuable bioactives with antithrombotic, anticoagulant, anti-inflammatory, antioxidant, and anticancer activities. Polysaccharides from certain abalones have antithrombotic activity, comparable to that of heparin (Suleria and others 2017). Snail flesh extract has the potential to treat asthma and tuberculosis (Padmanabhan and Sujana 2008). The glucan extract from China white jade snail (*Achatina fulica*) and hot water extract of Isada krill have significant antioxidant activities, suggesting their potentials as dietary antioxidant (Liao and others 2014; Koomyart and others 2015). Ziconotide, a peptide found in marine cone snail, is approved for analgesic use (Cheung and others 2015). The extract of the snail (*Bellamia bengalensis*) is also valuable for its hepatoprotective activity (Gomes and others 2011). Anti-inflammatory and antiarthritic dietary supplements such as "Seatone" and "Lyprinol" from mussel are commercially available (Grienke and others 2014). Taurine present in crustaceans and mollusks has the potential to reduce risks of CHD, either alone or in combination with n-3 PUFA (SELFNutritionData).

Table 7–Various hazard categories associated with shellfish.

Hazard type	Description
Environmental	Microbial pathogens, parasites, biotoxins, heavy metals, and chemical pollutants such as PCBs, dioxins, dioxin-like polychlorinated biphenyls (dl PCBs), and polychlorinated dibenzofurans
Intrinsic	Allergens such as tropomyosin, myosin light chains, troponins, paramyosin, sarcoplasmic calcium-binding proteins, arginine kinase, hemocyanins, cholesterol
Process related	Antibiotics such as chloramphenicol, sulfonamide, tetracycline, erythromycin, streptomycin, and β-lactams used in farming. Additives such as allergy causing metabisulfite used to control melanosis

Hazards Associated with Shellfish

A food is safe when it poses a minimal health hazard to consumers. A hazard is defined as a biological, chemical, or physical agent in food, or a condition of food with the potential to cause an adverse health effect to the consumer. An estimate of the probability and severity of the hazard is considered risk. Hazards associated with shellfish encompass raw, fresh, minimally processed, packaged, prepared, and stored items. The clinical symptoms of these hazards are specific to the dose and the health status of the consumer, ranging from mild to life-threatening and chronic adverse reactions (Huss and others 2000, 2003). In recent times, consumers have become well aware of seafood-borne hazards. Surveys have shown that consumers are more concerned about chemical contaminants in foods, in comparison with microbial hazards, because chemicals are known to cause long-term adverse effects (Kher and others 2013). In the interest of consumer safety it is important to evaluate the various hazards associated with shellfish.

Shellfish-associated hazards can be broadly grouped as environmental, intrinsic, and process-related, as shown in Table 7. Table 8 categorizes hazards associated with various shellfish products, in the order of decreasing risk. Shellfish items, which are consumed raw without any cooking, are the most hazardous, while products consumed soon after thorough heat processing pose minimum

Table 8–Shellfish hazard categories in order of decreasing risks.

Category	Description	Example
1	Shellfish consumed raw without any cooking	Mollusks, including fresh and frozen mussels, clam, oysters
2	Nonheat processed raw shellfish products often consumed with additional cooking	Fresh/frozen crustaceans
3	Lightly preserved products (with <6% salt in water phase, pH > 5.0)	Salted marinated, fermented, cold smoked shellfish.
4	Semipreserved products (salt > 6%) or pH < 5.0 with added preservatives	Salted, marinated shellfish, fermented items, caviar
5	Mildly heat-processed (pasteurized, cooked, hot smoked) products	Precooked, breaded items.
6	Heat processed shellfish products	Canned, retort-pouch sterilized items.

Source: Adapted from Huss and others (2000).

microbial hazards. This section briefly discusses various shellfish-borne hazards and measures to control these hazards.

Environmental hazards

Environmental hazards form a major class of hazards. These are caused by exposure of shellfish to microbial pathogens, parasites, biotoxins, heavy metals, pesticides, and other chemical pollutants from their habitats.

Pathogenic microorganisms

Microbial hazards are important with respect to the safety of shellfish species because they are prone to contamination by a variety of microorganisms. Major pathogenic organisms implicated in seafood-borne diseases include *Salmonella* spp. such as *Salmonella enteritidis, Salmonella paratyphi,* and *Salmonella typhimurium,* also *Shigella* spp., enterohemorrhagic and cytoxin-producing strain of *Escherichia coli* (*E. coli* serotype O157:H7), *Campylobacter* spp., *Vibrio* spp., *Aeromonas* spp., *Plesiomonas* spp., *Yersinia enterocolitica*, C*lostridium botulinum,* and *Listeria monocytogenes*. Pollution of coastal waters can result in contamination of bivalve shellfish with human enteric viruses, such as hepatitis A virus, norovirus, calicivirus, and astrovirus (Lalitha and Thampuran 2006; Roldan and others 2011; Leroi 2014; Jennings and others 2016). Table 9 indicates bacterial pathogens involved in shellfish-borne illnesses, minimal doses required for their infection and clinical symptoms.

Salmonella spp. including *Salmonella typhi* and *S. paratyphi* are responsible for high mortality rates (Amagliani and others 2012). Pathogens, including *Salmonella* spp. and *Shigella* spp., *Vibrio vulnificus, Vibrio parahemolyticus, Vibrio cholera*, and *C. botulinum* Type E, have been isolated from freshly caught crustaceans and mollusks, most likely contaminated by unhygienic harvest waters (Anonymous 2003). Bivalves are more prone to contamination because they are suspension feeders that filter phytoplankton, zooplankton, viruses, bacteria, and inorganic matter from contaminated water (Oliveira and others 2011). The risks may be further complicated, since many of these pathogens remain viable in chilled products. For example, the pathogenic *V. parahemolyticus, V. vulnificus,* and *V. cholera* can grow at 8 °C (Leroi 2014). *V. parahemolyticus*, a natural inhabitant in estuarine marine water, has been recognized as the leading causative agent of seafood-borne illness (Wang and others 2015). Hu and Chen (2016) observed that the resistance of these pathogenic microorganisms to antibiotics can further add to risk. The authors observed that 78% to 93% of strains of *Vibrio parahaemolyticus* isolated from 10 species of commonly consumed crustaceans and other shellfish in China exhibited resistance to ampicillin, rifampin, and streptomycin. About 75% of the isolates displayed resistance to more than 1 antibiotic, and also tolerance to heavy metals such as copper, lead, and cadmium.

C. botulinum can be present in marine sediments. *C. botulinum* types B, E, and F are frequently found in marine animals in cold or temperate waters. *Aeromonas hydrophila,* an agent of foodborne diarrheal disease, produces a wide range of cytotoxic enterotoxins and hemolysins (Khora 2014). Hepatitis A virus spreads through raw or undercooked shellfish and can cause liver disease (Sanchez 2015). Annually more than 1.4 million new cases of hepatitis A occur worldwide (WHO 2010). Nonindigenous pathogens such as *L. monocytogenes* and *Staphylococcus aureus* can be present in cooked products, as a result of abuse of processing, handling and/or storage conditions (Anonymous 2003). The habit of consumption of raw or lightly cooked bivalves increases pathogen-associated risks (WHO 2010; Karunasagar 2014; Khora 2014; WHO 2015).

Parasites

Food-associated parasites are recognized as a threat to food safety and human health. Flatworms, roundworms, and protozoa can infest the body of marine, freshwater, as well as farm-raised shellfish. Roundworms, called nematodes, are the most common parasites found in marine organisms and include *Ascaris* spp., *Trichuris* spp., and *Trichinella* spp. Other parasites are tapeworms such as *Diphyllobothrium* spp. and trematodes (*Chlonorchis* spp., particularly *C. sinensis*, *Opisthorchis* spp., *Heterophyes* spp., *Metagonimus* spp., *Nanophyetes* spp., and *Paragonimus* spp.) which are found in freshwater crustaceans. Anisakids are roundworms found in marine crustaceans and cephalopods. These parasites may embed in the intestinal wall of shellfish, and can be transmitted to humans. Animal parasites, such as *Cryptosporidium* spp., may also contaminate shellfish harvesting waters. Increasing globalization of the food supply, the trend of consuming raw, and the general ignorance about parasites are responsible for this hazard (Higashi 1985; Gajadhar 2015).

Biotoxins

Harmful algal bloom, popularly known as "red tide," may occur in the coastal waters, and may be quite hazardous due to the proliferation of poisonous algae such as dinoflagellates and diatoms. Shellfish, while feeing on these algae, accumulate their toxins. Toxin-contaminated shellfish may be found in temperate and tropical waters, typically after the "red tide." The Codex Alimentarius Standard has classified algal toxins into 5 groups, based on their chemical structures: (i) saxitoxin (STX), (ii) okadaic acid (OA, a polyether toxin), (iii) domoic acid (DA, a cyclic amino acid), (iv) brevetoxin (BTX, a cyclic polyether toxin), and (v) azaspiracid (AZA, a polyether toxin). An additional toxin group was also considered, tetrodotoxin (TTX), due to its emergence in shellfish. These toxins are known to cause 4 types of syndromes: (i) paralytic shellfish poisoning (PSP), (ii) diarrhetic shellfish poisoning (DSP), (iii) amnesic shellfish poisoning (ASP), and (iv) neurotoxic shellfish poisoning (NSP). PSP is caused by STX and TTX groups; DSP by OA and AZA groups; ASP by DA group; and NSP by BTX group (FAO 2004). PSP is associated with the consumption of clams, mussels, oysters, scallops, lobsters, and crabs, while scallops, clams, and blue mussels can be carriers of DSP. NSP can be present in oysters, clams, mussels, and cockles. Another toxin, yessotoxin, has been found in scallop and mussel (FAO 2004). Consumption of toxin-contaminated seafood by

Table 9–Seafood borne illnesses associated with bacterial pathogens.

Pathogenic bacteria	Seafood vector	Minimal dose for infection[a]	Clinical symptoms
Vibrio paramolyticus	Crustaceans	10^5 to 10^6	Diarrhea, nausea, vomiting
V cholera	Shellfish	10^2 to 10^6	Abdominal pain, vomiting diarrhea, dehydration, and possible death
Clostridium botulinum type E	Shellfish, smoked	0.01 to 1.0 mg toxin per gram	Paralysis, diarrhea, death
C. perfringens	Sporadic incidences	10^5 to 10^8	Diarrhea, seldom lethal
Aeromonas hydrophila	Shellfish	10^5 to 10^6	Vomiting, diarrhea
Listeria monotycogenes	Raw seafood, smoked, salted	$>10^2$	Diarrhea, vomiting, nausea
Bacillus cereus	Seafood, squid, prawn	10^6 to 10^9	Diarrhea, nausea, vomiting
Salmonella spp	Shrimp, mollusks	$>10^2$	Fever, headache, nausea, vomiting, abdominal pain, and diarrhea
Shigella	Mollusks	10^1 to 10^2	Severe diarrhea, cramps, vomiting
Yersinia enterocolitica	Shellfish	10^7 to 10^9	Diarrhea, vomiting, fever
Escherichia coli	Shellfish	10^1 to 10^9, depends on strain	Diarrhea, fever
Staphylococcus aureus	Contamination from infected persons	10^5 to 10^6	Diarrhea, cramps, vomiting

[a] Colony forming units/g raw shellfish meat.
Source: Adapted from Lalitha and Thampuran.(2006).

humans primarily results in acute gastrointestinal and neurological manifestations and leading to allergic reactions. These have been attributed to the effects of the toxins on sodium and calcium channels, the enzymes, sodium–potassium ATPase, and protein phosphatises (Garthwaite 2000; Kalidas and Anand 2006; Wang 2008; Khora 2014). DSP toxins in shellfish may be capable to increase cancer risk (Hernandez and others 2008). Annually, more than 50000 algal toxin-related incidents with an overall mortality rate of 1.5% have been reported globally (Wang 2008). The lethal effect of toxins is expressed as mouse unit, which is defined as the minimum amount of purified toxin (in micrograms) required to kill mouse of 20 g in 1 min, when 1.0 mL of a solution of extract at pH 4.0 is injected interperitoneally (Kalidas and Anand 2006).

Heavy metals

Industrial spills and sewage discards in coastal waters contaminate shellfish with toxic heavy metals, such as mercury (Hg), arsenic (As), cadmium (Cd), and lead (Pb). It is well known that chronic exposure to Hg, As, Cd, and Pb can cause adverse health effects (WHO 2015). Mercury is ubiquitous in the environment, which enters the air during fossil-fuel combustion, mining, smelting, solid-waste incineration, and other industrial activities. The metal exists in biological systems in elemental (metallic), inorganic (such as mercuric chloride), and organic forms (such as methylmercury [MeHg]; and ethylmercury [EtHg]). Inorganic mercury is converted to MeHg by microorganisms, which then enters the food chain and is bioconcentrated in the liver, gills, ink or skin of the seafood. Exposure to even small amounts of MeHg by pregnant women may affect fetal neurological development (Karunasagar 2014; WHO 2015; Seafish 2017). A recent collaborative study involving 8 countries showed that monomethyl mercury (MMG) in mussel, squid, and crab claw, and also some teleosts ranged from 0.035 to 3.58 μg/g, d. wt. Mussel had lowest MMG concentration (Valdersnes and others 2016). Global surveys indicated that intake of MeHg from shellfish and other seafood by women and infants in certain regions exceeded the reference value (Sheehan and others 2014).

Arsenic exists as highly toxic organic compounds in algae, which are consumed by shellfish. The metal interferes with several enzymes and causes oxidative stress as well as immune, endocrine, and epigenetic effects (Khora 2014). Lead occurs primarily in inorganic form in the environment. Human exposure is mainly via food and water. Lead can cause developmental neurotoxicity in children and cardiovascular effects in adults (European Food Safety Authority, EFSA 2010; Khora 2014). Cadmium can cause kidney damage, whereas lead causes neurotoxicity especially in children. A survey showed that flesh of mollusks had Hg, Cd, and Pb at levels of 0.44, 0.49, and 0.1 μg/g, w. wt., respectively. The corresponding values for the metals in raw cephalopods were 0.27, 0.50, and 0.12 μg/g. Squid meat accumulated selenium up to 1.2 μg/g raw meat; mollusks carried copper at 37.4 μg/g and zinc at 42 μg/g. Cuttlefish can accumulate significant amounts of potassium, calcium, manganese, iron, copper, and zinc from polluted marine environments (Akpan and others 2009). Octopus, squid, and cuttlefish from the Mediterranean Sea harbored heavy metals, their hepatopancreas showing higher concentrations than flesh. Highest concentrations of metals were found in octopus, namely: Hg, 0.44; Cd, 0.49; Pb, 0.10; Cu, 37.4; and Zn, 42.4 μg/g, w. wt. The contents (μg/g, w. wt.) for cuttlefish were: Hg, 0.27; Cd, 0.50; and Pb, 0.12, while squid tended to accumulate lower amounts of metals, especially Hg. The contents (μg/g, w. wt) were: Hg, 0.11; Cd, 0.30; Pb, 0.05; and Se, 1.18. Cr was uniformly distributed among the various species at 0.38% to 0.43 μg/g, w. wt. (Storelli and others 2010). Another study reported that cuttlefish meat had As, Cd, and Pb at concentrations of 2.2, 0.28, and 0.02 μg/kg, w. wt., respectively, while mercury was below the detection limit (Wen and others 2015).

Chemical pollutants

Polychlorinated biphenyls (PCBs), carcinogenic dioxins (polychlorinated dibenzo-*p*-dioxins, PCDDs), dioxin-like PCBs (dl PCBs), and polychlorinated dibenzofurans are by-products in the manufacture of herbicides and pesticides. They are also formed during volcanic eruptions, forest fires, and from incomplete combustion during waste incineration. These compounds are collectively referred as persistent organic pollutants (WHO 2015). Short-term exposure of humans to high levels of dioxins may result in skin lesions, such as patchy darkening of the skin, and altered liver function. Long-term exposure is linked to impairment of the immune system, the developing nervous system, and the endocrine system as well as reproductive functions. Chronic exposure of animals to dioxins has resulted in several types of cancer

(James 2013; WHO 2015). The toxicity of the PCBs and dioxin congeners is expressed as Toxin Equivalency (TEQ) (FAO/WHO 2016). Domingo (2016) observed that cooking procedures that release fat from a seafood product can reduce the concentrations of these fat-soluble organic contaminants

Hazards due to intrinsic factors

Shellfish allergy. Food allergy is due to the ability of molecules (antigens) present in the food to interact with immunological specific antibodies in the human body. Allergy symptoms in predisposed individuals depend on properties of the allergens such as their molecular size, chemical complexity, and genetic capacity of the host. Of the different types of allergies, Type I allergy is mediated by food proteins (Sathe and others 2016). Shrimp, lobster, and crab are common allergenic seafood items. The proteins, namely, tropomyosin, the enzyme arginine kinase, hemocyanins, paramyosin, myosin light chains, troponins, tropomyosin, and sarcoplasmic calcium-binding proteins are responsible for shellfish allergy (Fernandes and others 2015).

Content of cholesterol. Cholesterol in the body is transported by LDL and high-density lipoprotein (HDL), present in the blood. The presence of the LDL form of cholesterol in blood is associated with atherosclerosis, while the HDL form is inversely related to the development of atherosclerosis. As mentioned earlier, shellfish generally contains significant levels of cholesterol (Table 1). There is a general concern that consumption of shellfish may lead to deposits of LDL in the arteries leading to atherosclerosis (Wardlaw and Smith 2009). Cooking decreased cholesterol content of crab meat, but did not reduce it in shrimp or oyster (Krishnamoorthy and others 1979).

Process-related hazards

Processed shellfish products may carry pathogenic organisms if the processing treatment is not adequate to eliminate them. Most cases of botulism are associated with products subjected to inadequate thermal treatment (Leroi 2014). Besides botulism, listeriosis, cholera, and hepatitis A virus may be present in inadequately cooked, smoked, fermented, and pickled products, which are all usually consumed without further processing (Jay and others 2000). Listeria outbreaks are generally attributed to chilled ready-to-eat foods. These foods will not be generally subjected to a thorough heat treatment and therefore allow growth of *L. monocytogenes.* The majority of *Listeria* spp. isolated from aquatic products belongs to serotype 1/2a (Jami and others 2014).

Melanosis (black spot formation) is a problem in shrimp, lobster, and scallop that adversely affects their appearance and hence the commercial value. Melanosis is caused by oxidation of phenols by the enzyme polyphenol oxidase to quinone that eventually polymerizes to black, high-molecular-weight melanins. Chilling shellfish does not prevent melanosis, but slows it down only. In the Norway lobster (*N. norvegicus*), black spot appears within the 1st 4 d after capture and increases gradually throughout storage (Edmonds 2006). The common practice to control melanosis is dipping the shellfish in dilute aqueous solution of sodium metabisulfite; however, high concentrations of this chemical are frequently used by the processors, thereby leaving appreciable residual sulfite (SO_2) in the edible portions. The chemical has been recognized to cause allergic reactions, particularly in asthma patients (Nirmal and others 2015).

Hazards related to farmed shellfish. Shellfish is generally cultured in protected coastal areas that are usually under pressure from other human activities, leading to exposure of the shellfish to various hazards (Smaal and Wijsman 2010). These hazards include contamination of shellfish by pathogenic microorganisms, parasites, toxin-producing organisms, and also chemical pollutants. A bacterial disease, known as early mortality syndrome, has been a major cause for losses in shrimp aquaculture in Southeast Asia caused by a unique strain of the *V. parahaemolyticus* (Reed and Royales 2014). The viral disease “white spot syndrome” has continued to cause annual losses up to U.S.$ 1 billion, since its emergence in the 1990s (Jennings and others 2016). Tropical countries suffer greater losses in aquaculture during disease outbreaks, thereby presenting a major problem for food production and security (Leung and Bates 2013).

Contaminants in farmed shellfish include a range of chemicals such as veterinary pharmaceuticals (antibiotics, parasitical treatments, anesthetics), disinfectants (used to decontaminate equipment and eggs), and other biocidal chemicals such as formalin (used to control diseases), feed additives (such as flesh pigments), among others. Use of antibiotics (including chloramphenicol, sulfonamide, tetracycline, erythromycin, streptomycin, β-lactams, and sulfonamides) to prevent diseases in farms constitutes serious public health hazards leading to possible emergence of antibiotic resistance (Holmström and others 2003; Hu and Chen 2016). A recent survey showed that from 2006 to 2011 about 200 of 730 samples of retail aquacultured fishery products (including clam and shrimp) were positive for *Salmonella* spp. Thirty-eight serovars were identified in the 217 *Salmonella* isolates. Of the *Salmonella* spp., about 70% were resistant to at least 1 antimicrobial drug, while 43% were multidrug resistant. Resistance of the isolates against other antibiotics were: sulfonamides (57%), tetracycline (34%), streptomycin (29%), ampicillin (24%), and nalidixic acid (21%) (Zhang and others 2015). The Hong Kong oyster (*C. hongkongensis*) is widely farmed in estuarine waters, and has been found to accumulate Cu and Zn in their soft tissues (Gao and Wang 2014). It is well recognized that chemical pollutants are grossly accumulated in farm sediments, causing high levels of accumulation in bottom living animals such as shrimp (Swapna and others 2012).

Measures to Control Consumer Hazards

Safe food is of utmost importance in the interest of public health. Food safety can be ensured to a great extent with a combination of technology, and stringent quality standards, coupled with constant vigilance by regulatory bodies. The key elements of shellfish biosecurity include adequate diagnostic and detection methods to monitor pathogens, disinfection and pathogen eradication methods, applications of the Hazard Analysis Critical Control Point (HACCP) system, Good Management Practices (GMP), practical guidance, and appropriate legislative controls (Soares and others 2016; UK FSA 2017). HACCP is a 7-step management system that addresses food safety through the analysis and control of biological, chemical, and physical hazards from raw material production, procurement, handling to manufacturing, distribution, and consumption of the processed product (National Advisory Committee on Microbiological Criteria for Foods, NACMCF 1998; Huss and others 2000; Tzouros and Aravanitoyannis 2007).

Handling procedures for shellfish have been briefly mentioned earlier. Depuration for 2 d significantly reduces contaminated metals such as lead in bivalves. The health status of bivalves during depuration can be monitored by their glycogen content (Anacleto and others (2015). Depuration also significantly reduces contaminated pathogens from shellfish, although it is less effective to reduce hepatitis A to a significant level (Sanchez 2015). Commercial processing methods are generally inadequate to completely inactivate hepatitis A virus. For example, cooking of clam and oyster below 70 °C for approximately 47 s, which is employed for opening up their shells, could not annihilate hepatitis A virus (Sanchez 2015). Physical, chemical, and biological intervention strategies to control *Salmonella* spp., *Shigella* spp., *Vibrio* spp., *L. monocytogenes, C. botulinum,* viruses such as hepatitis A, and other microorganisms are available. These include time/temperature control, control of pH, control of water activity, and the use of preservatives, fermentation, drying, and salting (Anonymous 2003; Wang and others 2015). An integrated process of cooking and vacuum-cooling enhances the microbiological quality of mussel (Cavalheiro and others 2013). Growth of *C. botulinum* type E can be controlled by maintaining the temperature below 3.3 °C (Jay and others 2000). HHP treatment at 500 MPa for 2 min at 0 °C significantly reduced nonspore-forming pathogenic microorganisms from oysters (Lingham and others 2016). Exposure to ionizing radiations (gamma rays, machine-generated electron beams, or X-rays) provides an effective safeguard against most microbial and parasitic hazards. Gram-negative pathogens such as *Vibrio* and *Salmonella* are comparatively more sensitive to radiation than Gram-positive bacteria. These pathogens have D_{10} values (radiation dose required for 90% reduction) as low as 1 kGy in comparison with high D_{10} values of Gram-positive organisms. Bacterial spores such as those of *C. botulinum* are more resistant to radiation than their vegetative cells. Microorganisms in frozen samples will have higher D_{10} values (Venugopal and others 1999; Sommers and Rajkowski 2011). The U.S. FDA has amended its current food additive regulations to allow the use of ionizing radiation at a maximum permitted dose of 6.0 kGy to inactivate foodborne pathogens in crustaceans and extend their shelf-life (Center for Food Safety and Applied Nutrition, CFSAN 2014). Irradiation at this dose (6.0 kGy) caused a collateral reduction of hepatitis A virus levels along with *Vibrio* spp. (Praveen and others 2013). Radiation treatment can also inactivate parasites in shellfish (Sommers and Rajkowski 2011). Irradiation can also be combined with traditional processes such as depuration, thermal treatment, and others (Venugopal 2006). Candling, trimming belly flaps, and physically removing cysts can reduce parasitic hazards. Heating at 55 °C for 1 min or by frozen storage for 24 h at −20 °C can inactivate parasites (NACMCF 1998; Codex Alimentarius 2016). The hazard of sulfite allergy associated with sulfite-treated shellfish can be addressed by using sulfite alternatives such as *Xyrex—Prawnfresh, Everfresh,* and *Melacide SC20* (Edmonds 2006).

Addressing the problem of harmful algal bloom causing presence of toxins in shellfish requires integrated coastal zone management, particularly regular monitoring of algae in shellfish-growing waters and closing of shell harvesting areas, whenever toxin levels in shellfish exceed limits (Khora 2014). Marine toxins being mostly nonprotein in nature processing operations such as cooking, smoking, drying, and salting have limited scope to destroy them in the harvested shellfish. The kinetics of thermal destruction of scallop toxin is qualitatively similar to that of microorganisms (Indrasena and Gill 1999). Avoiding the offending food is the best defense for sensitive individuals to prevent allergy (Sathe and others 2016). Heat treatment enhanced antibody reactivity to prawn allergens including tropomyosin, myosin light chain, sarcoplasmic calcium binding protein, and other prawn allergens (Kamat and others 2014). Chitin, the principal component of the crustacean shell and its derivatives, can address allergic responses by enhancement of innate immune system, alteration of Th1/Th2 balance forward to Th1 cells, inhibition of IgE production, and suppression of mast cell degranulation (Vo and others 2015).

Processing treatments, such as HHP, washing, cooking, and others can significantly decrease heavy metals such as Cd content in Pacific oyster (Rasmussen and Morrissey 2007). It is interesting to note that selenium present in shellfish is beneficial because it can assist in elimination of mercury. Bjerregaard and Christensen (2012) reported that selenite, seleno-cysteine, and seleno-methionine, when administered via food, displayed dose-dependent elimination of MeHg from marine shrimp. Analyses of 485 samples of the 43 most frequently consumed shellfish and fish species in Spain showed that these items possessed beneficial Hg-to-Se ratios and Se-associated health benefit values (Olmedo and others 2013).

A study on the dietary influence of cholesterol from shrimp on levels of plasma lipoproteins (LDL and HDL) found that, although consumption of steamed shrimp up to 300 g/d supplied an amount of 590 mg dietary cholesterol, it did not impair the lipoprotein profile. While the shrimp consumption increased LDL by 7.1%, the beneficial HDL was increased by 12.1% in comparison with a baseline diet. In contrast, consumption of 2 large eggs per day resulted in an intake of 581 mg dietary cholesterol, raising LDL by 10.2% (De Oliveira e Silva and others 1996). Another study reported that, while diets containing oyster, clam, or crab lowered LDL triglycerides, and cholesterol, diet containing shrimp did not change the ratio of LDL to HDL (Childs and others 1990). Animal feeding studies reported a beneficial role of hydrolyzed fish proteins in the reduction of plasma total cholesterol together with increase blood HDL (Wergedahl and others 2004). In addition, noncholesterol sterols present in shellfish have the potential to reduce the absorption of cholesterol (Dong 2001). These studies suggested that intake of cholesterol from shellfish is unlikely to adversely affect the consumer's overall lipoprotein profile. It may be mentioned that in the human body about two-thirds of cholesterol is metabolically formed, while the remaining is derived from foods. The cholesterol contents in shellfish can be beneficial for normolipidemic populations for proper functioning of the cell membranes and also as precursor for steroid hormones and bile acids (Wardlaw and Smith 2009). The 2015 *U.S. Dietary Guidelines* Advisory Committee observed absence of clear connection between the intake of cholesterol and level of the sterol in the blood. The Committee also found absence of adequate evidence for a quantitative limit for dietary cholesterol specific to the *Dietary Guidelines.* The high blood cholesterol level among consumers could be linked to their intake of saturated fat, suggesting a need to restrict intake of saturated fat (Anonymous 2015). It may be further pointed out that shellfish have lower atherogenic (a condition having inflamed plaques on the insides of arteries) and thrombogenic (condition causing coagulation of blood) indices (Bono and others 2012). An atherogenic index of 0.36 for shrimp, in comparison with atherogenic indices of 1.0, 0.7, and 0.67 for mutton, beef, and pork, has been reported (Dayal and others 2013).

The measures to ensure safety of farmed shellfish encompass proper site selection, licensing, and certification of shellfish growing waters based on their hygienic quality, closure of farms in cases of extreme contamination, regular monitoring of algae and pathogens in the ponds, and proper sewage treatment. In addition, control of stocking density, feed quality, shucking, and depuration, and also introduction of a HACCP protocol will result in improved quality of farmed shellfish (Patterson and others 1997; Su and Liu 2013; Codex Alimentarius 2013). Rapid methods to

Table 10–Key areas to address shellfish associated hazards.

Classification, licensing, and certification of shellfish farms
Regular monitoring of environment and water quality
GMP implementation
HACCP implementation
Standard Operating Procedures (SOP)
Analytical testing: microbiological, physical, chemical, sensory.
Process verification and validation to ensure product safety
Traceability
Bar-coding of products
Labeling of products for consumer awareness
Import alerts, recall, and crisis management programs
Employee training and education

detect pathogenic microorganisms, biotoxins, allergens, heavy metals, and antibiotics can significantly contribute to shellfish safety (Fernandes and others 2015; FAO/WHO 2016; Santos and Ramos 2016). A multiplex polymerase chain reaction-denaturing high-performance liquid chromatography (MPCR-DHPLC) method has been developed for the rapid detection of the pathogens *V. cholerae, V. parahemolyticus, V. vulnificus, Vibrio rmimicus, Vibrio alginolyticus*, and *L. monocytogenes* in aquatic products (Zhan and others 2015). Bar-coding and phylogenetic analysis can be used to detect multiple species of shellfish, such as crabs, in commercial products (Haye and others 2012). Food traceability (defined as the ease with which a product can be traced throughout the supply chain) tracks down the history of food across the entire supply chain, so that recalls of unsafe food items can be conducted efficiently (Dandage and others 2017). Labeling products can warn consumers of the health risks involved in consuming raw or under cooked shellfish. Farmer awareness about the potential farming-related hazards, such as adverse effects of antibiotics, offers significant scope to improve product safety (Swapna and others 2012). It has been recognized that shellfish culture, shellfish restoration, and nature conservation are related issues that need to be addressed (Smaal and Wijsman 2010). Table 10 indicates the key areas to control shellfish associated hazards.

Monitoring of food safety by regulatory bodies

In recent times, the importance of an integrated, multidisciplinary approach to food safety and quality throughout the entire food chain has been recognized. International and national regulatory bodies with defined rules and standards have established appropriate control programs to ensure consumer safety in fish trade. There is particular emphasis on the FAO's strategy to promote international harmonization and capacity building (Ababouch 2006). The WHO extends guidance to the bivalve shellfish industry to minimize the risks to human health (WHO 2010,2015). The FAO, WHO, and other international organizations provide scientific assessments on foodborne hazards in compliance with international standards, guidelines, and recommendations promulgated in the Code of Practice for Live and Raw Bivalve Mollusks (Codex Alimentarius 2013). The Global Aquaculture Alliance (GAC) provides advice on best aquaculture practices (Lee and Connelly 2006). The *Fish Inspector*, published by FAO/INFOFISH regularly informs on global developments with respect to seafood inspection, quality control, and technology (www.infofish.org; accessed 2017 January 6). The NSA is an international organization concerned with the biology, ecology, production, economics, and management of shellfish resources (National Shellfisheries Association, NSA 2017).

In the United States, agencies responsible for food safety include the FDA within the Dept. of Health and Human Services, the Food Safety and Inspection Service (FSIS) and the Animal and Plant Health Inspection Service (APHIS), within the Dept. of Agriculture (USDA), and the NMFS, within the Dept. of Commerce. The FDA is responsible for protecting consumers against impure, unsafe, and mislabeled foods. The Environmental Protection Agency (EPA) is involved in setting standards and tolerances for pesticide residues in foods and feed. The EPA also provides regular advisories and guidelines on shellfish and fish consumption. Other agencies having food safety responsibilities include the Centers for Disease Control and Prevention (CDC), and the Natl. Institutes of Health (NIH) (Holley 2011). The Natl. Shellfish Sanitation Program (NSSP) of the FDA provides guidance for the sanitary control of molluscan shellfish intended for human consumption (FDA 2015). A recently published guide provides to the U.S. seafood industry information related to Food Safety Modernization Act, HACCP, and quality-related problems in seafood (Zimmerman 2016).

In the EU, the EU-funded database assists seafood and aquaculture industries to collate data on contaminants and to devise safety measures (ECsafeSEAFOOD 2017). Imports of fish and seafood are strictly regulated in the EU, requiring health certification and traceability (Seafish 2017). Key developments in EU fisheries policy and fish hygiene are regularly notified in the newsletter FishFiles Lite (Megapesca (Portugal) 2017). The U.K. Food Standards Agency provides guidance to reduce the risk of vulnerable groups to food hazards (U.K. FSA 2017). The Health Canada and the Canadian Food Inspection Agency share food safety responsibility in the country. In Australia and New Zealand, a comprehensive food standards code is enforced by the state and territory governments and also by food enforcement agencies (FSANZ 2017). The Food Safety Law addresses the safety issues associated with aquaculture in China (Broughton and Walker 2010).

Worldwide, shellfish safety is thoroughly ensured taking into consideration the health guidance values for contaminants, stipulated by regulatory agencies (Hellberg and others 2012; Khora 2014). The Joint Expert Committee on Food Additives (JECFA) of the FAO/WHO at its 72nd meeting established a Provisional Tolerable Weekly Intake (PTWI) for inorganic mercury of 4 μg/kg body weight (bw) (JECFA 2010). The PTWI values (μg/kg bw/d) for MeHg, Cd, and Pb have been reported 0.23, 0.83, and 3.6, respectively (Hellberg and others 2012). The U.S. FDA has set an action level of 1.0 ppm for MeHg corresponding to an intake of 0.5 μg MeHg/kg bw/d (Hellberg and others 2012). Current European standards regulate the levels of microbiological agents, phycotoxins, and chemical contaminants in food (Guéguen and others 2011). The EFSA Panel on Contaminants in the Food Chain (CONTAM) has established a tolerable weekly intake (TWI) of 4 μg/kg/bw of inorganic mercury, 1.3 μg/kg/bw of MeHg (EFSA 2012), and 2.5 μg/kg/bw of cadmium (EFSA 2011). The Codex Standard for Live and Raw Bivalve Mollusks (Codex Standard 292–2008) has limits for biotoxins including STX, OA, DA, brevitoxin, and AZA groups (Codex Alimentarius 2013). The maximum permitted levels of PSP toxins per killogram of flesh of mollusk are as follows: STX group, $\leq$0.8 mg of STX equivalent; OA group, $<$0.16 mg of OA equivalent; DA group, $<$20 mg DA; BTX group, $<$200 mouse units or equivalent; and AZA group, $<$0.16 mg AZA (FAO/WHO 2016). The EU Directive 91/492/EEC permits maximum level of PSP toxin at 0.8 mg STX equivalent/kg shellfish and non-dl PCBs at 200 ng/g w wt (EC 2009). Australia, New Zealand, Canada, and Japan recommend 200 OA equivalent/kg shellfish (Khora 2014).

Recent surveys have shown that, in general, the levels of heavy metals and chemical pollutants in shellfish species are too low to pose serious hazards. About two-thirds of the total seafood supply, and 9 of the 11 most consumed shellfish (and also fish) in the U.S. had low or very low Hg contents (Groth 2010). Average exposure of U.K. consumers to 24 metal elements including Hg from fishery and other food items has generally declined over time, and it has remained at levels too low to cause major health concerns (Rose and others 2010). Analysis of 47 fishery products by the U.K. FSA revealed that shellfish harbor very low levels of environmental pollutants, far below the European regulatory limits (Seafish 2017). Regular consumption of mussel at 1 kg/wk for 26 wk by 102 healthy men and women aged 48 to 76 y did not cause concern regarding Hg, As, and Cd levels in their blood (Outzen and others 2015). Average concentrations of heavy metals in 6 commercial cephalopod species of South Korea were in the order of Al > As > Cd > Pb > Hg. All the metal contents were within the regulatory guidelines, and did not pose any threat to consumers (Nho and others 2016). Detailed studies showed that shellfish contamination from seawater offers a rather low risk to the general French population (Guéguen and others 2011). Heavy metal contents in shellfish products in a popular seafood market in India were within the maximum levels prescribed by the EU and the FDA (Sivaperumal and others 2007). Storelli's group has conducted detailed surveys on heavy metal contamination of Mediterranean shellfish. They found that a 70-g serving of mollusks resulted in intake of 0.89 μg/kg/bw of Cd, which corresponded to 35.6% of PTWI of the metal (Storelli and others 2010). Bioaccessibility of heavy metals is an important factor in determining their hazards, which has received much attention in recent years. Gao and Wang (2014) observed that bioaccessibility varies with metals. They found that silver from farmed oyster had the lowest oral bioaccessibility (38.9% to 60.8%), whereas the values for Cu and Zn range from 72.3% to 93%; Cd and Pb had values between those of Ag and Zn. Cano-Sancho and others (2015) reported that arsenic from seafood was bioaccessible up to 89%, while Hg was less than 50% bioaccessible. Fernandes and others (2008) examined the chemical pollutants PCDD/F and PCB in the most commonly consumed shellfish in Scotland including mussels, oysters, and scallops. The estimated adult dietary intakes of these pollutants arising from the consumption of a typical portion of these foods in combination with an average U.K. diet were in the range of 0.5 to 0.6 pg (WHO toxic equivalent, TEQ) (2005)/kg bw/d. These values were within the tolerable daily intake of 2.0 pg (WHO toxic equivalent, TEQ) (2005)/kg bw/d, endorsed by an Independent Expert Committee on Toxicology of Chemicals in Food, Consumer Products and the Environment. Khora (2014) has listed 16 countries that have regulatory programs to protect public health from marine toxin contamination.

The presence of antibiotics in farmed seafood has declined since the 1980s due to farmer awareness campaigns, regulatory control, and also to the introduction of vaccines against bacterial diseases (Jennings and others 2016). The national chemical residue monitoring programs that operate in the U.S. and Canada report compliance with maximum residue level (MRL) (Holley 2011). According to EU Directive 2003/89/EC, allergen labeling is a requirement for all foodstuffs produced in the European Community (Edmonds 2006). Sulfite is currently listed in Annex III Part B of Directive 95/2/EC as an authorized food additive and is labeled E223 with a maximum permitted residue in crustacean products set at 150 ppm (Edmonds 2006).

Local control authorities are involved in the classification of mollusks and other shellfish growing areas, based on the possibility of environmental contaminations (Jennings and others 2016). The 4 components of the U.S. FDA cooperative program include classification of shellfish growing areas based on water quality, inspection to ensure sanitary measures, control of harvesting from prohibited waters, and laboratory analysis (FDA 2017). The U.K. Food Standard Agency provides guidance on the hygienic production of shellfish (U.K. FSA 2017). Traceability of shellfish in supply chains is essential to ensure product safety. The food traceability regulations of 21 Organizations for Economic Co-Operation and Development (OECD) countries provide practical guidance on seafood authenticity (Charlebois and others 2014; Zhang and Bhatt 2014). A recently launched cloud-based mobile application is expected to increase the transparency of the supply chain (Dandage and others 2017).

In addition to the control measures discussed above, consumer alerts are also provided by regulatory authorities. Recent alerts were related to the presence of PSP in oysters, *V. cholerae* in frozen cooked prawns, and *C. botulinum* in canned seafood, which were issued by the International Food Safety Authorities Network (INFOSAN) developed by the WHO and the FAO (INFOSAN 2014/2015). Alerts were also issued by the U.S. FDA after detection of the presence of drug residues from unapproved animal drugs and/or unsafe food additives in imported aquaculture shrimp and prawn (FDA 2016). Such alerts are also issued by the Food Standard Agency (U.K. FSA 2017) and by the EU (Megapesca (Portugal) 2017). These measures have significant roles to protect the consumer from contaminated shellfish.

Risk-Benefit Analysis

The risks and benefits of shellfish consumption have been evaluated in several studies. An expert consultation under the lead of FAO and WHO, which evaluated risks and benefits of shellfish (and other seafood) concluded that consumption of seafood provided energy, protein, and a range of other important nutrients, including the long-chain n-3 PUFAs. There is absence of probable or convincing evidence of CHD associated with MeHg At levels of maternal exposure to dioxins (from seafood and other dietary sources) that do not exceed the Provisional Tolerable Monthly Intake (PTMI) of 70 pg/kg/bw, established by the Joint Expert Consultation; neurodevelopmental risk for the fetus is negligible (FAO/WHO 2011; James 2013). Sirot and others (2012) reported that consumption of approximately 50 g/wk of mollusks, crustaceans (and also lean fish) supplied the consumer the recommended intake levels of n-3 PUFA, selenium, and iodine while MeHg, Cd, dioxins, polychlorobiphenyls, Zn, Ca, and Cu remained below the tolerable upper intake values. Olmedo and others (2013) reported that the daily intakes of heavy metals from 43 most frequently consumed shellfish (and also fish) represented very low percentages of their reference values, ranging from 0.1% (Se) to 3.9% (Cu) for a person weighing 60 kg. Cardoso and others (2010) observed that, although the consumption levels of seafood (consisting of many species) by individuals varied considerably from 140 g/wk in the U.K. to 628.5 g/wk in Iceland, the probability of exceeding the PTWI value for MeHg was low, ranging from 0.04% in the U.K. to 9.61% in Iceland. A recently developed app, "BeneFISHiary," has been reported as useful to the consumer to provide simultaneous information on the contents of selenium, omega-3 fatty acids, and mercury in fishery products (Pirckle 2016). Studies on risk-benefit analysis have concluded that the benefits of nutrients grossly outweigh the risks among the general population, when a variety of shellfish, whether marine or freshwater origin, farmed or wild, is consumed (IOM 2007; Hellberg and others 2012; Oehlenschläger 2012; Olmedo and others 2013; Weichselbaum and others 2013; Domingo 2016). The Second Intl. Conference on Nutrition (ICN2), held in Rome in November 2014, confirmed the importance of shellfish and other seafood as a source of nutrition and health (FAO 2016).

Conclusions

Shellfish items can satisfy the dietary requirements of many nutrients. Their nutrient contents depend on species, habitats, harvesting season, feed, and other factors. The health benefits derived from shellfish also depend on specific type of the species consumed, the frequencies of consumption, as well as quantities consumed. There is the potential for producing nutritionally enriched farmed shellfish using feeds fortified with nutrients such as long-chain PUFAs, vitamins, and carotenoids. Although carotenoids have been commercially used to improve the color of farmed shellfish, particularly shrimp, the nutritional value of shellfish fed with astaxanthin, β-carotene, and other carotenoids has yet to be explored. Shellfish items including abalone, mussel, and snail possess compounds, which have interesting bioactivities, such as immune-modulating, anti-inflammatory, antioxidant, ACE-inhibitory, and other functions. There is the potential for uses of these components for the development of functional foods. The nutritional benefits of shellfish can be derived without undue concerns of their safety. Shellfish-associated hazards are manageable at the stages of harvesting, farming, processing, storage, distribution, and consumption, with appropriate intervention strategies and control measures by national and international regulatory agencies. With increasing globalization, international trade, and rising consumer interests, a need persists for constant vigil to ensure sustainable supply of a safe shellfish.

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Author Contributions

The layout of the review was constructed by V.V. Both V.V. and K.G. searched the literature. V.V. developed the manuscript. V.V. and K.G. edited, and V.V. revised the final manuscript.

Conflict of Interest

The authors declare no conflict of interest.

References

Ababouch L. 2006. Assuring fish safety and quality in international fish trade. Marine Poll Bull 53:561–8.

Abeynayake R, Mendis E. 2014. Anti-aging and immuno-enhancing properties of marine bioactive compounds. In: Kim SK, editor. Seafood science: advances in chemistry technology and applications. Boca Raton, Fla.: CRC Press. p 262–75.

Akpan I, Ama-Absai D, Adebiyi FM, Obiajunwa EI. 2009. Assessment of potential toxic elements pollution of marine environment using African cuttlefish *Sepia bertheloti* from the Gulf of Guinea as an environmental bio-indicator. Toxicol Environ Chem 91:947–54.

Alfonso C, Bandarra NM, Nunes L, Cardoso C. 2016. Tocopherols in seafood and aquaculture products. Crit Rev Food Sci Nutr 56:128–40.

Amagliani G, Brandt G, Schiavano GF. 2012. Incidence and role of *Salmonella* in seafood safety. Food Res Intl 45:780–8.

Anacleto P, Maulvault AL, Nunes ML, Carvallo ML, Rosa R, Marques A. 2015. Effects of depuration on metal levels and health status of bivalve mollusks. Food Control 47:493–501.

Anonymous. 2003. Analysis of microbial hazards related to time/temperature control of foods for safety. Compr Rev Food Sci Food Saf 2:33–41.

Anonymous. 2015. US Dept. of Health and Human Services and the US Dept. of Agriculture 2015–2020 Dietary guidelines for Americans. 8th ed. Available from: http://healthgov/dietaryguidelInes/2015/guidelines/. Accessed 2016 July 3.

Anthony JE, Hadgis PN, Milam RS, Herzfeld GL, Taper LJ, Ritchey SJ. 1983. Yields, proximate composition and mineral content of finfish and shellfish. J Food Sci 48:313–4.

Antony SP, Bright Singh IS, Philip R. 2010. Molecular characterization of a crustin-like putative antimicrobial peptide, F-crustin from the Indian white shrimp. Fish Shellfish Immunol 28:216–22.

Ashie INA, Smith JP, Simpson BK, Haard NF. 1996. Spoilage and shelf-life extension of fresh fish and shellfish. Crit Rev Food Sci Nutr 36:87–121.

Babu CM, Chakraborti R, Raja K, Sambasivarao S. 2008. Effect on carotenoid pigments during enzymatic extraction and freeze drying of caroteno-protein from shrimp head waste. LWT - Food Sci Technol 41:227–35.

Balachandran KK. 1976. On the carotenoid pigments In Indian prawns. Fishery Technol (India) 13:121–5.

Bao B, Prasad AS, Beck FW, Fitzgerald JT, Shell D, Bao CW, Singh T, Cardozo LJ. 2010. Zinc decreases C-reactive protein lipid peroxidation and inflammatory cytokines in elderly subjects: a potential implication of zinc as an atheroprotective agent. Am J Clin Nutr 91:1634–41.

Barrento S, Marques A, Teixeira B, Anacleto P, Vaz-Pirez P, Nunes ML. 2009a. Effect of season on the chemical composition and nutritional quality of the edible crab *Cancer pagurus*. J Agric Food Chem 57:10814–24.

Barrento S, Marques A, Teixeira B, Vaz-Pirez P, Nunes ML. 2009b. Nutritional quality of the edible tissues of European lobster *Homarus gammarus* and american lobster *Homarus americanus*. J Agric Food Chem 57:3645–52.

Berge J-P, Barnathan G. 2005. Fatty acids from lipids of marine organisms: molecular diversity; role as biomarkers; biologically active compounds and economical aspects. Adv Biochem Engr/Biotechnol 96:49–125.

Bindu J, Joseph G. 2005. Mussel meat products technology. India: Central Inst. of Fisheries Technology. Available from: http://www.ciftres.in. Accessed 2016 September 3.

Binsi P, Shamasundar B, Dileep A. 2007. Physicochemical and functional properties of proteins from green mussel *Perna viridis* during ice storage. J Sci Food Agric 87:245–54.

Bjerregaard P, Christensen A. 2012. Selenium reduces the retention of methyl mercury in the brown shrimp, Crangon crangon. Environ Sci Technol 46:6324–29.

Bogard JR, Thilsted SH, Marks GC, Wahab MA, Hossain MAR, Jakobsen J, Stangoulis J. 2015. Nutrient composition of important fish species in Bangladesh and potential contribution to recommended nutrient intakes. J Food Comp Anal 42:120–33.

Bono G, Gai F, Peiretti PG, Badalucco C, Palmegiano GB. 2012. Chemical and nutritional characterization of the Central Mediterranean giant red shrimp *Aristaeomorpha foliacea*: influence of trophic and geographical factors on flesh quality. Food Chem 130:104–10.

Bragagnolo N, Rodriguez-Amaya DB. 2001. Total lipid cholesterol and fatty acids of farmed freshwater prawn (*Macrobrachium rosenbergii*) and wild and marine shrimp (*Penaeus brasiliensis*, *P. schimitti*, *Xiphopenaeus kroyeri*). J Food Comp Anal 14:359–69.

Broughton EI, Walker DG. 2010. Policies and practices for aquaculture food safety in China. Food Policy 35:471–8.

Calder PC. 2014. Very long chain omega-3 (n-3) fatty acids and human health. Eur J Lipid Sci Technol 116:1280–300.

Cano-Sancho G, Perello G, Maulvault AL, Marques A, Nadal M, Domingo JL.2015. Oral bio-accessibility of arsenic mercury and methylmercury in marine species commercialized in Catalonia Spain and health risks for the consumers. Food Chem Toxicol 86:34–40.

Cardoso C, Bandarra N, Lourenco H, Alonso C, Nunes M. 2010. Methylmercury risks and EPA + DHA benefits associated with seafood consumption in Europe. Risk Anal 30:827–40.

Cavalheiro D, Schmidt FC, Rodrigues LGG, Leitempergher F, Laurindo JB. 2013. Processing of Perna perna mussels using integrated process of cooking and vacuum cooling. J Food Proc Engr 36:192–201.

Center for Food Safety and Applied Nutrition (CFSAN). 2014. FDA allows ionizing radiation to control food-borne pathogens in crustaceans. U.S. Food and Drug Administration Press Release. Available from: https://www.fda.gov/food/newsevents/constituentupdates/ucm392860.htm. Accessed 2017 January 5.

Chakraborty K, Chakkalakal SJ, Joseph D, Asokan PK, Vijayan KK. 2016a. Nutritional and antioxidative attributes of green mussel, *Perna viridis* L from the southwestern coast of India. J Aquatic Food prod Technol 25: 968–85.

Chakraborty K, Chakkalakal SJ, Joseph D, Joy M. 2016b. Nutritional composition of edible oysters (*Crassostrea madrasensis* L) from the southwest coast of India. J Aquatic Food Prod Technol 25:1172–89.

Chandrasekharan M. 1994. Methods for pre-processing and freezing of shrimps: a critical evaluation. J Food Sci Technol (Mysore) 31:441–6.

Charlebois S, Sterling B, Haratifar S, Naing SK. 2014. The food traceability regulations of 21 organizations for economic co-operation and development OECD countries: comparison of global food traceability regulations and requirements. Compr Rev Food Sci Food Saf 13:1104–23.

Cherif S, Frikha F, Gargouri Y, Miled N. 2008. Fatty acid composition of green crab (*Carcinus mediterraneus*) from the Tunisian Mediterranean coasts. Food Chem 111:930–33.

Cheung RCF, Ng TB, Wong JH. 2015. Marine peptides: bioactivities and applications. Marine Drugs 13:4006–43.

Cheung S-H, Kim E-K, Hwang J-W, Kim Y-S, Lee JS, Moon S-H, Jeon B-T, Park P-J. 2013. Purification of a novel peptide derived from a shellfish Crassostrea gigas and evaluation of its anticancer property. J Agric Food Chem 61:11442–6.

Childs MT, Dorsett CS, King IB. 1990. Effects of shellfish consumption on lipoproteins in normolipidemic men. Am J Clin Nutr 51:1020–7.

Choe E, Min DB. 2006. Chemistry and reactions of reactive oxygen species in foods. Crit Rev Food Sci Nutr 46:1–35.

Christensen, JK, Kane GM, Farmery AK. 2017. The barriers and drivers of seafood consumption in Australia: a narrative literature review. Intl J Cons Stud 41:299–311.

Chuyen VH, Eun J-B. 2017. Marine carotenoids: bioactivities and potential benefits to human health. Crit Rev Food Sc Nutr 57:2600–10.

Codex Alimentarius. 2013. Codex standards for live and raw bivalve mollusks. Codex STAN 292–2008. Available from: www.codexalimentarius.org. Accessed 2015 September 1.

Codex Alimentarius. 2016. Guidelines on the application of general principles of food hygiene to the control of food-borne parasites. CAC/GL 88–2016. Available from: www.fao.org/fao-who-codexalimentarius/sh-proxy/zh/?lnk. Accessed 2017 July 8.

Dandage K, Badia-Melis R, Ruiz-García L. 2017. Indian perspective in food traceability: a review. Food Control 17:217–27.

Dayal JS, Ponniah AG, Khan HI, Madhu Babu EP, Ambasankar K, Vasagham KPK. 2013. Shrimps—a nutritional perspective. Current Sci (India) 104:1487–91.

Dean RT, Fu S, Stocker R, Davies M J. 1997. Biochemistry and pathology of radical mediated protein oxidation. Biochem J 324:1–18.

Department of Health, UK. 2013. Nutrient analysis of fish and fish products. Available from: www.dh.gov.uk/publications. Accessed 2017 February 4.

de Carvalho CCCR, Caramujo MJ. 2017. Carotenoids in aquatic ecosystems and aquaculture: a colorful business with implications for human health. Front Mar Sci 4:1–13.

De Oliveira e Silva ER, Seidman CE, Tian JJ, Hudgins LC, Sacks FM, Breslow J. 1996. Effects of shrimp consumption on plasma lipoproteins. Am J Clin Nutr 64:712–7.

Domingo JL. 2016. Nutrients and chemical pollutants in fish and shellfish: balancing health benefits and risks of regular fish consumption. Crit Rev Food Sci Nut 56:979–88.

Dong FM. 2001. The nutritional value of shellfish. Washington Sea Grant: WSG-MR 09-03. Seattle, Wash.: U.S. Natl. Oceanic and Atmospheric Administration. p 4–8.

Dridi S, Romdhane MS, Elcafsi M. 2007. Seasonal variation in weight and biochemical composition of the Pacific oyster (*Crassostrea gigas*) in relation to the gametogenic cycle and environmental conditions of the Bizert lagoon Tunisia. Aquaculture 263:238–48.

ECsafeSEAFOOD. 2017. Priority environmental contaminants in seafood. Available from: http://www.ecsafeseafooddbase.eu/. Accessed 2017 February 13.

Edmonds M. 2006. Sodium metabisulphite alternatives SR583. Seafish Industry Authority, UK. Available from: http://www.seafish.org/media/Publications/sodium_metabisulphite_rpt.pdf. Accessed 2017 January 5.

Elmadfa I, Meyer AL. 2017. Animal proteins as important contributors to a healthy human diet. Ann Rev Anim Biosci 5:111–31.

Emelyanov A, Fedoseev G, Krasnoschekova O, Abulimity A, Trendeleva T, Barnes, PJ. 2002. Treatment of asthma with lipid extract of New Zealand green-lipped mussel: a randomized clinical trial. Eur Resp J 20:596–600.

European Food Safety Authority (EFSA). 2010. EFSA Panel on contaminants in the food chain CONTAM. Scientific opinion on lead in food. EFSA J 8(4):1570. https://doi.org/10.2903/j.efsa.2010.1570.

European Food Safety Authority (EFSA). 2011. Statement on tolerable weekly intake for cadmium. EFSA Panel on contaminants in the food chain. EFSA J 9(2):1975. SN 1831–4732. https://doi.org/10.2903/j.efsa.2011.1975.

European Food Safety Authority (EFSA). 2012. Panel on contaminants in the food chain. Scientific opinion on the risk for public health related to the presence of mercury and methylmercury in food. EFSA J 10(12): 2985. https://doi.org/10.2903/j.efsa.2012.2985.

Food and Agriculture Organization (FAO). 2004. Marine biotoxins. Available from: http://www.fao.org/docrep/007/y5486e/y5486e00.htm. Accessed 2016 July 5.

Food and Agriculture Organization (FAO). 2016. The state of world fisheries and aquaculture: contributing to food security and nutrition for all. 200 p. Available from: http://www.fao.org/3/a-i5555e.pdf. Accessed 2016 September 1.

Food and Agriculture Organization (FAO)/INFOODS. 2016. Global food composition database for fish and shellfish. Version 10-uFiSh10. Available from: http://www.fao.org/3/a-i6655e.pdf. Accessed 2017 January 6.

Food and Agriculture Organization/World Health Organization (FAO/WHO). 2004. Vitamin and mineral requirements in human nutrition. 2nd ed. Available from: http://appswhoInt/iris/bitstream/10665/42716/1/9241546123pdf. Accessed 2017 January 2.

Food and Agriculture Organization/World Health Organization (FAO/WHO). 2011. Report of the joint expert consultation on the risks and benefits of fish consumption. Fishery and Aquaculture Report. No. 978, 50 p. Available from: http://www.fao.org/docrep/014/ba0136e/ba0136e00.pdf. Accessed 2016 September 5.

Food and Agriculture Organization/World Health Organization (FAO/WHO). 2016. Toxicity equivalency factors for marine biotoxins associated with bivalve mollusks. 108 p. Available from: http://www.fao.org/3/a-i5970e.pdf. Accessed 2017 February 2.

Food and Drug Administration (FDA). 2008. Seafood nutrition facts. Available from: https://www.fda.gov/downloads/Food/GuidanceRegulation/ucm063478.pdf. Accessed 2016 April 2.

Food and Drug Administration (FDA). 2015. National Shellfish Sanitation Program guide for the control of molluscan shellfish. Revision. Available from: https://www.fda.gov/food/guidanceregulation/federalstatefoodprograms/ucm2006754.htm. Accessed 2017 February 4.

Food and Drug Administration (FDA). 2016. Import alert #16-136 dated 4/18/2016. Available from: http://wwwaccessdatafdagov/CMS_IA/importalert_1153html. Accessed 2017 February 6.

Food and Drug Administration (FDA). 2017. Cooperative program ensures safe shellfish. Available from: https://www.fda.gov/ForConsumers/ConsumerUpdates/ucm180996.htm. Accessed 2017 February 10.

Fernandes A, Dicks P, Mortimer D, Gem M, Smith F, Driffield M, White S, Rose M. 2008. Brominated and chlorinated dioxins PCBs and brominated flame retardants in Scottish shellfish: methodology, occurrence and human dietary exposure. Mol Nutr Food Res 52:238–49.

Fernandes TJR, Costa J, Oliviera MBPP, Mafra I. 2015. An overview on fish and shellfish allergens and current methods of detection. Food Agric Immunol 26:848–69.

Finley JW. 2007. Increased intakes of selenium-enriched foods may benefit human health. J Sci Food Agric 87:1620–29.

Friedman K. 1996. Nutritive value of proteins from different food sources a review. J Agric Food Chem 44:6–29.

U.K. Food Standard Agency (FSA). 2017. Fish and shellfish. Available from: www.foodgov.uk. Accessed 2016 December 4.

Food Standards Australia and New Zealand (FSANZ). 2011. Food nutrient database. Available from: http://www.foodstandards.gov.au/science/monitoringnutrients/ausnut/foodnutrient/Pages/default.aspx. Accessed 2017 August 6.

Food Standards Australia and New Zealand (FSANZ). 2017. Food standards code. Available from: www.foodstandards.gov.au/code. Accessed 2017 February 5.

Fu Y, Li G, Zhang X, Xing G, Hu X, Yang L, Li D. 2015. Lipid extract from hard-shelled mussel (*Mytilus coruscus*) improves clinical conditions of patients with rheumatoid arthritis: a randomized controlled trial. Nutrients 7:625–45.

Gajadhar A. 2015. Introduction to food-borne parasites. In: Gajadhar A, editor. Food-borne parasites in the food supply web: occurrence and control. Amsterdam, The Netherlands: Woodhead Publishing. p 3–9.

Gao S, Wang W-X. 2014. Oral bio-accessibility of toxic metals in contaminated oysters and relationships with metal internal sequestration. Ecotoxicol Environ Saf 110:261–8.

Garthwaite I. 2000. Keeping shellfish safe to eat: a brief review of shellfish toxins, and methods for their detection. Trends Food Sci Technol 11:235–44

Gigliotti J, Jaczynski J, Tou JC. 2008. Determination of the nutritional value, protein quality and safety of krill protein concentrate isolated using an isoelectric solubilization/precipitation technique. Food Chem 111:209–14.

Gobbo Del LC, Imamura F, Aslibekyan S, Marklund M, Virtanen JK, Wennberg M, Yakoob MY, Chiuve SE, dela Crauz L, Frazier-Wood AC, Fretts AM, Guallar E, Matsumoto C, Prem K, Tanaka T, Wu JHY, Zhou X, Helmer C, Ingelsson E, Yuan J-M, Barberger-Gateau P, Campos H, Chaves PHM, Djousse LG, Giles GG, Gómez-Aracena J, Hodge AM, Hu FB, Jansson J-H, Johansson I, Khaw K-T, Koh W-P, Lemaitre RN, Lind L, Luben RN, Rimm EB, Risérus U, Samieri C, Franks PW, Siscovick DS, Stampfer M, Steffen LM, Steffen BT, Tsai MY, van Dam RM, Voutilainen S, Willett WC, Wood-ward M, Mozaffarian D. 2016. ω-3 polyunsaturated fatty acid biomarkers and coronary heart disease: pooling project of 19 cohort studies. JAMA 176(8):1155–66.

GOED. 2017. Organization of EPA and DHA Omega-3s. Available from: http://wwwgoedomega3com. Accessed 2017 January 12.

Gogus U, Smith C. 2010. n-3 omega fatty acids: a review of current knowledge. Intl J Food Sci Technol 45:417–36.

Gokoglu N, Yerlikaya P. 2015. Seafood chilling, refrigeration and freezing: science and technology. Chichester, UK: Wiley Blackwell. p 255.

Gomes A, Alam MA, Datta P, Battacharya S, Gomes A. 2011. Hepatoprotective activity of the edible snail Bellamia bengalensis flesh extract in carbon tetrachloride induced hepatotoxicity in rats. J Ethnopharmacol 138:228–32.

Gopakumar K. 1997. Biochemical composition of Indian food fishes. India: Central Inst. of fisheries technology. Available from: http://www.cift.res.in. Accessed 2016 May 3.

Grienke U, Silke J, Tasdemir D. 2014. Bioactive compounds from marine mussels and their effects on human health. Food Chem 142:48–60.

Groth E III. 2010. Ranking the contributions of commercial fish and shellfish varieties to mercury exposure in the United States: implications for risk communication. Environ Res 110:226–36.

Guéguen M, Amiard J-C, Arnich N, Badot P-M, Claisse D, Guérin T, Vernoux J-P. 2011. Shellfish and residual chemical contaminants: hazards monitoring and health risk assessment along French coasts. Rev Environ Contam Toxicol 213:55–111.

Gunasekaran J, Kannuchamy N, Kannaiyan S, Chakraborti R, Gudipati V. 2015. Protein hydrolysates from shrimp (*Metapenaeus dobsoni*) head waste: optimization of extraction conditions by response surface methodology. J Aquatic Food Prod Technol 24:429–42.

Hamed I, Ozogul F, Ozogul Y, Regenstein JM. 2015. Marine bioactive compounds and their health benefits: a review. Compr Rev Food Sci Food Saf 14:446–65.

Harnedy PA, FitzGerald RJ. 2012. Bioactive peptides from marine processing waste and shellfish: a review. J Funct Foods 4:6–24.

Hasler CM. 1998. Functional foods: their role in disease prevention and health promotion. J Food Technol 52:63–7.

Haye PA, Segovia NI, Vera R, Gallardo María de los A, Escárate CC. 2012. Authentication of commercialized crab-meat in Chile using DNA barcoding. Food Control 25:239–44.

Hellberg RS, De Witt CAM, Morrissey MT. 2012. Risk-benefit analysis of seafood consumption: a review. Compr Rev Food Sci Food Saf 11:490–517.

Hernández Becerra JA, Ochoa Flores AA, Valerio-Alfaro G, Rodriguez JS, Estrada MT, Garcia HS. 2014. Cholesterol oxidation and astaxanthin degradation in shrimp during sun drying and storage. Food Chem 14:5832–9

Hernandez JM, Rodal VL, Costas E, Hermandez JM. 2008. Shellfish consumption: a major risk factor for colorectal cancer. Med Hypotheses 70:409–12.

Higuera-Ciapara I, Felix-Valenzuela L, Goycoolea FM. 2006. Astaxanthin: a review of its chemistry and applications. Crit Rev Food Sci Nutr 46:185–96.

Higashi N. 1985. Food-borne parasites transmitted to man from fish and other foods. Food Technol 39(3):65–9.

Holley RA. 2011. Food safety challenges within North American free trade agreement NAFTA partners. Compr Rev Food Sci Food Saf 10:131–42.

Holmström K, Gräslund S, Wahlström A. 2003. Antibiotic use in shrimp farming and implications for environmental impacts and human health. Intl J Food Sci Technol 38:255–66.

Hossain Z, Takahashi K. 2012. Health benefits of bio-functional marine lipids. Proceedings of the 2nd International Congress on Seafood Technology on Sustainable Innovative and Healthy Seafood. Anchorage, Alaska: Food and Agriculture Organization, Univ. of Alaska. p 209–14.

Huss HH, Reilly A, Ben Embarek PK. 2000. Prevention and control of hazards in seafood. Food Control 11:149–56.

Huss HH, Ababouch L, Gram L. 2003. Assessment and Management of Seafood Safety and Quality. Technical Paper No. 444. Rome: Food and Agriculture Organization.

Hussein G, Sankava U, Goto H, Matsumoto K, Watanabe H. 2005. Astaxanthin a carotenoid with potential in human health and nutrition. J Nat Prod 69:443–7.

Hu Q, Chen L. 2016. Virulence and antibiotic and heavy metal resistance of *Vibrio parahaemolyticus* isolated from crustaceans and shellfish in Shanghai China. J Food Prot 79:1371–7.

Indrasena WM, Gill, TA. 1999. Thermal degradation of paralytic shellfish poisoning toxins in scallop digestive glands. Food Res Intl 32:49–57.

Institute of Medicine (IOM). 2007. Seafood choices: balancing benefits and risks. In: Nesheim MC, Yaktine AL, editors. Food and Nutrition Board, Institute of Medicine of the National Academies. Washington DC: Natl. Academies Press. p 722.

International Network of Food Safety Authorities (INFOSAN). 2014/2015. Activity Report 2014/2015. Food and Agriculture Organization/World Health Organization. Available from: http://www.who.int/foodsafety/areas_work/infosan/en/. Accessed 2016 September 6.

James D. 2013. Risks and benefits of seafood consumption.GLOBEFISH Research Program. Vol. 108. Rome, Italy: Food and Agriculture Organization. p 28.

Jami M, Ghanbari M, Zunabovic M, Kneifel W. 2014. *Listeria monocytogenes* in aquatic food products: a review. Compr Rev Food Sci. Food Saf 13:798–813.

Jay JM, Loessner, MJ, Golden DA. 2000. Modern food microbiology. 7th ed. Gaithersburg, Md.: Springer. p 790.

JECFA. 2010. Report of the Joint FAO/WHO Expert Consultation on the risks and benefits of fish consumption, Rome. Available from: http://www.fao.org/docrep/014/ba0136e/ba0136e00.pdf. Accessed 2017 August 12.

Jennings S, Stentiford JD, Leocadio AM, Jeffery KR, MetCalfe JD, Katsiadaki J, Auchterlonie NA, Managi SC, Pinnegar JK, Ellis T, Peeler EJ, Luisetti P, Baker-Austin C, Brown M, Catachpole TL, Clyne FJ, Dye SR, Edmonds NJ, Hyder K, Lee J, Lees DN, Morgan OC, O'Brien CM, Oldtmann B, Posen PE, Santos AR, Taylor NGH, Turner AD, Townhill BL, Verner-Jeffreys DW. 2016. Aquatic food security: insights into challenges and solutions from an analysis of interactions between fisheries aquaculture, food safety, human health, fish and human welfare economy and environment. Fish Fisheries 17:893–38.

Kalidas C, Anand PS. 2006. Seafood biotoxins and general consideration to public health. Indian Food Ind 25:52–6.

Kalogeropoulos N, Andrikopoulos NK, Hassapidou M. 2004. Dietary evaluation of Mediterranean fish and mollusks pan-fried in virgin olive oil. J Sci Food Agric 84:1750–8.

Kamat SD, Rahman AMA, Voskamp A, Kormoda K, Rolland JM, O'hehir RE, Lopata AE. 2014. Effect of heat processing on antibody reactivity to allergen variants and fragments of black tiger prawn: a comprehensive allergenomic approach. Mol Nutr Food Res 58:1144–55.

Kanazawa A. 2001.Sterols in marine invertebrates. Fish Sci 67:997–9.

Karnjanapratum S, Benjakul S, Kishimura H, Tsar V-H. 2013. Chemical composition and nutritional value of Asian hard clam Meretrix lusoria from the coast of Andaman Sea. Food Chem 141:4138–45.

Karunasagar I. 2014. Global bivalve production; marketing and safety issues. In: McLeod C, Farrel H, Hallegraeff G, Zammit A, editors. Global bivalve production; marketing and safety issues. Sydney, Australia: Proceedings of the 9th International Conference on Molluscan Shellfish Safety. p 2–5.

Kaulman A, Bohn T. 2014. Carotenoids inflammation and oxidative stress: implications of cellular signaling pathways and relation to chronic disease prevention. Nutr Res 34:907–29.

Kher SV, Jonge JD, Wentholt MTA, Deliza R, de Andrade JC, Cnoozen HJ, Luijckx NBL, Frewer LJ. 2013. Consumer perceptions of risks of chemical and microbiological contaminants associated with food chains: a cross-national study. Intl J Cons Stud 37:73–83.

Khora S. 2014. Health risks associated with seafood. In: Kim SK, editor. Seafood science: advances in chemistry, technology and applications. Boca Raton, Fla.: CRC Press. p 483–570.

Kim S-K, Venkatesan J. 2015. Introduction to seafood science. In: Kim SK, editor. Seafood science: advances in chemistry, technology and applications. Boca Raton, Fla.: CRC Press. p 1–13.

Koomyart I, Nagamizu H, Khuwijitjaru P, Kobayashi T, Shiga H, Yosh H, Adachi S. 2015. Compositions, flavor and antiradical properties of products from subcritical water treatment of raw Isada krill. Intl J Food Sci Technol 50:1632–9.

Kreuzer R. 1984. Cephalopods: handling processing and products. Fisheries Technical Paper 254. Rome, Italy: Food and Agriculture Organization. p 108.

Kris-Etherton PM, Harris WS, Appel LJ. 2002. Fish consumption fish oil omega-3 fatty acids and cardiovascular disease. Circulation 106: 2747–57.

Krishnamoorthy RV, Venkataramiah A, Lakshmi GJ, Biesiot P. 1979. Effects of cooking and of frozen storage on the cholesterol content of selected shellfish. J Food Sci 44:314–5.

Krzynowek J, Dentremont DL, Murphy J. 1989. Proximate composition and fatty acid and cholesterol content of squid *Loligo pealei* and *Illex illecebrosus*. J Food Sci 54:45–8.

Küçükgülmez A, Çelik M, Yanar Y, Ersoy B, Cikrikci M. 2006. Proximate composition and mineral contents of the blue crab Callinectes sapidus breast meat, claw meat and hepatopancreas. Intl J Food Sci Technol 41:1023–6.

Lalitha KV, Thampuran N. 2006. Seafood-borne bacterial pathogens. Fishery Technol (India):43:118–21.

Lee D, Connelly J. 2006. Global Aquaculture Alliance on best aquaculture practices: an industry prepares for sustainable growth sustainable development law and practice. Law Policy 7:60–62.

Leroi F. 2014. Role of bacteria in seafood products. In: Kim SK, editor. Seafood science: advances in chemistry technology and applications. Boca Raton, Fla.: CRC Press. p 397–432.

Leung TLF, Bates AE. 2013. More rapid and severe disease outbreaks for aquaculture at the tropics: implications for food security. J Applied Ecol 50:215–22.

Li G, Li J, Li D. 2010a. Seasonal variation in nutrient composition of *Mytilus coruscus* from China. J Agric Food Chem 58:7831–7.

Li N, Hu J, Wang S, Cheng J, Hu X, Lu Z, Lin Z, Zhu W, Bao Z. 2010b. Isolation and identification of the main carotenoid pigment from the rare orange muscle of the Yesso scallop. Food Chem 118:616–9.

Li G, Sinclair AJ, Li D. 2011. Comparison of lipid content and fatty acid composition in the edible meat of wild and cultured freshwater and marine fish and shrimps from China. J Agric Food Chem 59:1871–81.

Liao N, Chen S, Ye X, Zhong J, Ye X, Yin X, Tian J, Liu D. 2014. Structural characterization of a novel glucan from *Achatina fulica* and its antioxidant activity. J Agric Food Chem 62:2344–52.

Lin Y-H, Tsai J-H, Hung L-B, Pan BS. 2010. Hypocholesterolemic effect of compounded freshwater clam protein hydrolysate and Gracilaria. Food Chem 123:395–9.

Lingham TYM, Chen H, Karuna L, Handy CE, Zhao J, Wu C, Ozbay G. 2016. Effects of high hydrostatic pressure on the physical, microbial and chemical attributes of oysters Crassostrea virginica. J Food Sci 81:M1158–66.

Lordan S, Ross PR, Stanton C. 2011. Marine bioactives as functional food ingredients: potential to reduce the incidence of chronic diseases. Marine Drugs 9:1056–100.

Lou Q-M, Wang Y-M, Xue C-H. 2013. Lipid and fatty acid composition of two species of abalone Haliotis discus hannaiIno and Haliotis diversicolor. J Food Biochem 37:296–301.

Martin DE, Hall SG. 2006. Oyster shucking technologies: past and present. Intl J Food Sci Tech 41:223–32.

Mathew S, Ammu K, Viswanathan Nair PG, Devadasan K. 1999. Cholesterol contents of Indian fish and shellfish. Food Chem 66:455–61.

Maulvault AJ, Anacleto P, Lourenço HM, Carvallo ML, Nunes ML, Marques A. 2012. Nutritional quality and safety of cooked edible crab *Cancer pagurus*. Food Chem 133: 277–83.

Megapesca (Portugal). 2017. Technical information in food & fisheries policy & development. European Union Newsletter. Available from: http://megapesca.com/. Accessed 2017 January 3.

Mesko MF, Toralles IG, Hartwig CA, Coelho Jr GS, Muller AL, Bizzi CA, Mello PA. 2016. Bromine iodine contents in raw and cooked shrimp and its parts. J Agric Food Chem 64:1817–22.

Muth MK, Viator CL, Karns SA, Cajka JC, O'Neill M. 2013. Analysis of the costs and economic feasibility of requiring postharvest processing for raw oysters. Compr Rev Food Sci Food Saf 12:652–61.

Naczk M, Williams J, Brennan K, Chandrika L, Shahidi F. 2004. Compositional characteristics of green crab Carcinus maenas. Food Chem 88:429–34.

National Advisory Committee on Microbiological Criteria for Foods (NACMCF). 1998. Hazard analysis and critical control point: principles, application and guidelines. J Food Prot 61:1246–51.

National Marine Fisheries Service (NMFS). 1987. Proximate composition, energy, fatty acids, sodium, and cholesterol contents of finfish, shellfish and their products. In: Krzynowek J, Murphy J, editors. Technical Report No. 74. Washington DC: Natl. Oceanic and Atmospheric Administration. p 42.

National Shellfisheries Association (NSA). 2017. National Marine Fisheries Service Laboraty, Oxford, Md. Available at: http://www.shellfish.org. Accessed 2017 January 3.

Nettleton JA, Exler J. 1992. Nutrients in wild and farmed fish and shellfish. J Food Sci 57:257–60

Ngo DH, VO, TS, Ngo DN, Wijesekara I, Kim SK. 2012. Biological activities and potential health benefits of bioactive peptides derived from marine organisms. Intl J Biol Macromol 51:378–83.

Nho Y, Khan N, Choi JY, Kim JS, Park KS, Kim KS. 2016. Determination of toxic metals in cephalopods from South Korea. Anal Lett 49:1578–88.

Nirmal NP, Benjakul S, Ahmed M, Arafat YL, Panichayupakaranant P. 2015. Undesirable enzymatic browning in crustaceans: causative effects and its inhibition by phenolic compounds. Crit Rev Food Sci Nutr 55:1992–2003.

Nybakken JW. 2001. Marine biology: an ecological approach. 4th ed. Boston, Mass: Addison-Wessley Publishing. p 516.

Oehlenschläger J. 2012. Seafood: nutritional benefits and risk aspects. Intl J Vitamin Nutr Res 82:168–76.

Oliveira J, Cunha A, Castilho F, Romalde JM, Pereira MI. 2011. Microbial contamination and purification of bivalve shellfish: crucial aspects in monitoring and future perspectives—a mini-review. Food Control 22:805–16.

Olmedo P, Hernández AF, Pla A, Femia P, Navas-Arien A, Gil F. 2013. Determination of essential elements copper, manganese, selenium, and zinc in fish and shellfish samples Risk and nutritional assessment and mercury–selenium balance. Food Chem Toxicol 62:299–07.

Outzen M, Tjonneland A, Larsen EH. 2015. Effect of increased intake of fish and mussels on exposure to toxic trace elements in a healthy middle-aged population. Food Addit Contam Part A 32:1858–66.

Ozogul F, Kuley E, Ozogul Y. 2015. Sterol content of fish, crustacea and mollusk: effects of cooking methods. Intl J Food Prop 18:2026–41.

Ozogul O, Duysak O, Ozogul F, Ozkutuk AS, Tureli C. 2008. Seasonal effects in the nutritional quality of the body structural tissue of cephalopods. Food Chem 108:847–52.

Pacheco-Aguilar R, Marquez-Ríos E, Lugo-Sánchez ME, Garcia-Sanchez C, Martinez ANM, Ocaño-Higuera VM. 2008. Postmortem changes in the adductor muscle of Pacific lions-paw scallop Nodipecten subnodosus during ice storage. Food Chem 106:253–9.

Padmanabhan P, Sujana K. 2008. Animal products in traditional medicine from Attappady hills of Western Ghats. Ind J Trad Knowledge 7:326–9.

Papaioannou CD, SInanoglou VJ, Strati IF, Proestos C, Kyrana VK, Lougovois VP. 2016. Impact of different preservation treatments on lipids of the smooth clam Callista chione. Intl J Food Sci Technol 51:325–32.

Parisenti J, Beirão LH, Tramonte VLCG, Ourique F, da Silveira Britto CC, Moreira CC. 2011. Preference ranking of color in raw and cooked shrimp. Intl J Food Sci Technol 46:2558–61.

Passi S, Cataudella S, Di Marco P, De Simone F, Rastrelli L. 2002. Fatty acid composition and antioxidant levels in muscle tissue of different Mediterranean marine species of fish and shellfish. J Agric Food Chem 50:7314–22.

Patterson B, Goodrick B, Frost S. 1997. Controlling the quality of acquacultured food products. Trends Food Sci Technol 8:253–8.

Pirckle C. 2016. Benefits and risks of fish consumption provided by new app. Available from: https://manoahawaiiedu/publichealth/tag/catherIne-pirkle. Accessed 2017 February 3.

Praveen C, Dancho BA, Kingsley DH, Calci KR, Meade GK, Mena KD, Pillai SD. 2013. Susceptibility of marine norovirus and hepatitis a virus to electron beam irradiation in oysters and quantifying the reduction in potential infection risks. Appl Environ Microbiol 79:3796–801.

Rasmussen RS, Morrissey MT. 2007. The effects of processing methods and storage on cadmium levels in Pacific oysters Crassostrea gigas. J Aquatic Food Prod Technol 16:3–17.

Rayman MP. 2000. The importance of selenium to human health. Lancet 356:233–41.

Reed K, Royales S. 2014. Shrimp disease in Asia resulting in high US import prices. Global Econ 3(14):1–9.

Roldan EM, Rodríguez; EE, Vicente CN, Navajas MF-C, Abril OM. 2011. Microbial contamination of bivalve mollusks used for human consumption. J Food Safety 31:257–61.

Rosa R, Nunes ML. 2004. Nutritional quality of red shrimp *Aristeus antennatus* Risso, pink shrimp *Parapenaeus longirostris* Lucas and Norway lobster *Nephrops norvegicus* Linnaeus. J Sci Food Agric 8:89–94.

Rose M, Baxter M, Brereton N, Baskaran C. 2010. Dietary exposure to metals and other elements in the 2006 UK total diet study and some trends over the last 30 years. Food Addit Contam Part A 27:1380–404.

Ruiz-Capillas C, Moral A. 2004. Free amino acids in muscle of Norway lobster Nephrops novergicus L in controlled and modified atmospheres during chilled storage. Food Chem 86:85–91.

Sachindra NM, Bhaskar N, Mahendrakar NS. 2005a. Carotenoids in different body components of Indian shrimps. J Sci Food Agric 85:167–72.

Sachindra NM, Bhaskar N, Mahendrakar NS. 2005b. Carotenoids in crabs from marine and fresh waters of India. LWT - Food Sci Technol 38:221–25.

Sanchez G.2015. Processing strategies to inactivate hepatitis A virus in food products. Compr Rev Food Sci Food Saf 14:771–84.

Santos L, Ramos F. 2016. Analytical strategies for the detection and quantification of antibiotic residues in aquaculture fishes: a review. Trends Food Sci Technol 52:16–30.

Saskia M, Ruth V. 2014. Seafood and water management. Foods 3:622–31.

Sathe SK, Liu C, Zaffran VD. 2016. Food allergy. Ann Rev Food Sci Technol 7:191–220.

Scorletti E, Byrne CD. 2013. Omega-3 fatty acids, hepatic lipid metabolism and nonalcoholic fatty liver disease. Ann Rev Nutr 33:231–48.

Seafish. 2017. The nutritional benefits of shellfish Part 2 IPF _A081 Seafish Report No SR635_2, London. Available from: www.shellfish.org.uk. Accessed 2017 January 10.

SELFNutrition Data. Nutrition Facts. Available from: http://nutritiondataselfcom/facts/fInfish-and-shellfish-products/4174/2. Accessed 2015 September 15.

Shahidi F, Metusalach G, Brown JA. 1998. Carotenoid pigments in seafood and aquaculture. Crit Rev Food Sci Nutr 38:1–67.

Sheehan MC, Burke T A, Navas-Acien A, Breysse PN, McGready J, Fox MA. 2014. Global methylmercury exposure from seafood consumption and risk of developmental neurotoxicity: a systematic review. Bull World Health Organ 92:254–69F.

Sinanoglu VJ, Meimaroglou SM. 1998. Fatty acids of neutral and polar lipids of edible Mediterranean cephalopods. Food Res Intl 31:467–73.

Siriwardhana N, Kalupahana NS, Moustaid-Moussa N. 2012. Health benefits of n-3 polyunsaturated fatty acids: eicosapentaenoic acid and docosahexaenoic acid. Adv Food Nutr Res 65:211–22.

Sirot V, Leblanc JC, Margaritus I. 2012. A risk-benefit analysis approach to seafood intake to determine optimal consumption. Br J Nutr 107:1812–22.

Sivaperumal P, Sankar T, Viswanathan Nair PG. 2007. Heavy metal concentrations in fish, shellfish and fish products from the internal markets of India vis-à-vis international standards. Food Chem 102:612–20.

Soares NF, Vicente AA, Martins CMA. 2016. Food safety in the seafood industry: a practical guide for ISO 22000 and FSSC 22000 implementation. Chichester, UK: Wiley-Blackwell. p 200.

Sommers CH, Rajkowski R. 2011. Radiation inactivation of food-borne pathogens in frozen seafood products. J Food Prot 74:641–4.

Souci SW, Fachman W, Krant H. 2008. Food composition and nutrition tables. 7th ed. Stuttgart, Germany: Medpharm Scientific Publishers. p 1300.

Soumya R, Sachindra NM. 2015. Carotenoids from fishery resources. In: Sachindra NM, Mahendrakar NS, editors. Fish processing byproducts: quality assessment and applications. Houston, Tex.: Studium Press. p 273–98.

Smaal AC, Wijsman JWM. 2010. Exploitation and restoration of bivalve shellfish resources. Aquaculture Intl 18:1–2.

Sriket P, Benjakul S, Visessanguan W, Kijroongrojan K. 2007. Comparative studies on chemical composition: thermal properties of black tiger shrimp (*Penaeus monodon*) and white shrimp (*Peneaus vannamei*) meats. Food Chem 103:1199–207.

Storelli MM, Garofalo R, Giungato D, Giacominelli-Stuffler R. 2010. Intake of essential and non-essential elements from consumption of octopus cuttlefish and squid. Food Addit Contam Part B 3:14–8.

Su X-Q, Antons K, Li D, Nichols P. 2006. Seasonal variations of total lipid and fatty acid contents in the muscle of two Australian farmed abalone species. J Food Lipids 13:411–23.

Su Y-C, Liu C. 2013. Shellfish handling and primary processing. In: Boziaris IS, editor. Seafood processing: technology, quality and safety. Chistester, UK: John Wiley and sons. p 9–32.

Suleria HAR, Masci PP, Gobe G C, Osborne SA. 2017. Therapeutic potential of abalone and status of bioactive molecules: a comprehensive review. Crit Rev Food Sci Nutr 57:1742–8.

Surh J, Ryu JS, Kwon H. 2003. Seasonal variations of fatty acid compositions in various Korean shellfish. J Agric Food Chem 51:1617–22.

Swapna KM, Rajesh K, Lakshmanan PT. 2012. Incidence of antibiotic residues in farmed shrimps from the southern states of India. Ind J Geo-Marine Sci 41:341–7.

Tantasuttikul A, Kijroongrojana K, Benjakul S. 2011.Quality indices of squid *Photololigo duvaucelii* and cuttlefish *Hexaplex epiaaculeata* stored in ice. J Aquatic Food Prod Technol 20:129–47.

Tou JC, Jaczynski J, Chen Y-C. 2007. Krill for human consumption: nutritional value and potential health benefits. Nutr Rev 65:63–7.

Turan T, Kaya Y, Erdem ME. 2011. Proximate composition cholesterol and fatty acid content of brown shrimp (Crangon crangon L.1758) from Sinop Region, Black Sea. J Aquatic Food Prod Technol 20:100–07.

Tzouros NE, Aravanitoyannis IS. 2007. Implementation of hazard analysis critical control point (HACCP) system to the fish/seafood industry: a review. Food Res Intl 16:273–325.

U.S. Dept. of Agriculture (USDA). 2012. Food composition databases. USDA National Nutrient Database for Standard Reference. Available from: http://ndbnalusdagov/ndb/search/list. Accessed 2016 June 4.

Vaz-Pires P, Barbosa A. 2004. Sensory, microbiological, physical and nutritional properties of iced whole common octopus, *Octopus vulgaris*. LWT - Food Sci Technol 37:105–14.

Valdersnes S, Fecher P, Maage A, Julshamn K. 2016. Collaborative study on determination of mono methylmercury in seafood. Food Chem 194:424–31.

Venugopal V. 1993. Cook-chill process to extend refrigerated shelf life of peeled and deveined shrimp and white pomfret. Intl J Food Sci Technol 28:273–8.

Venugopal V. 2006. Seafood processing: adding value through quick freezing, retortable packaging and cook-chilling. Boca Raton, Fla.: CRC Press. p 524.

Venugopal V. 2009. Marine products for healthcare: functional and bioactive nutraceuticals from the ocean. Boca Raton, Fla.: CRC Press. p 527.

Venugopal V, Doke SN, Thomas P. 1999. Radiation processing to improve the quality of fishery products. Crit. Rev. Food Sci. Nutr. 39:391–440.

Venugopal V, Lele SS. 2014. Nutraceuticals from seafood processing waste. In: Kim SK, editor. Handbook of marine biotechnology. Gaithersburg, Md.: Springer. p. 1405–25.

Venugopal V, Shahidi F. 1996. Structure and composition of fish muscle. Food Rev Intl 12:175–97.

Vijaykrishnaraj M, Prabhasankar P. 2015. Marine protein hydrolysates: their present and future perspectives in food chemistry—a review. RSC Adv 5:34864–77.

Vo T-S, Ngo D-H, Kang KH, Jung WK, Kim SK. 2015. The beneficial properties of marine polysaccharides in alleviation of allergic responses. Mol Nutr Food Res 59:129–38.

Wall R, Ross RP, Fitzgerald GF, Stanton C. 2010. Fatty acids from fish: the anti-inflammatory potential of long-chain omega-3 fatty acids. Nutr Rev 68:280–9.

Wang DZ. 2008. Neurotoxins from marine dinoflagellates: a brief review. Marine Drugs 6:349–55.

Wang B, Li L, Chi C-F, Ma J-H, Luo H-Y, Xu Y-F. 2013. Purification and characterization of a novel antioxidant peptide derived from blue mussel (*Mytilus edulis*) protein hydrolysate. Food Chem 138:1713–9.

Wang W, Li M, Li Y. 2015. Intervention strategies for reducing *Vibrio parahaemolyticus* in seafood: a review. J Food Sci 80:R10–19.

Wardlaw GM, Smith AM. 2009. Contemporary nutrition. New York, N.Y.: McGraw-Hill. p 750.

Weichselbaum E, Coe S, Buttriss J, Stanner S. 2013. Fish in the diet: a review. Nutr Bull 38:128–77.

Wen J, Chen D, Zeng L, Wang Y, Tian Li, Lai J. 2015. Nutritional quality and safety of the important commercial cuttlefish *Sepia lycidas*. J Aquatic Food Prod Technol 24:101–11.

Wergedahl H, Liaset B, Gudbrandsen OA. 2004. Fish protein hydrolysate reduces plasma total cholesterol; increases the proportion of HDL cholesterol; and lowers acyl-CoA cholesterol-acyltransferase activity in liver of Zucker rats. J Nutr 134:1320–27.

World Health Organization (WHO). 2010. In: Rees G, Pond K, Kay D, Bartram J, Domingo JS, editors. Safe management of shellfish and harvest waters. Minimizing health risks from sewage-contaminated shellfish. World Health Organization. p 360.

Food Safety, World Health Organization (WHO). 2015. Available from: http://www.who.int/mediacentre/factsheets/fs399/en/. Accessed 2016 December 12.

Wu Y-X, Li W, Jin T. 2015. Preparation and characterization of protein hydrolysates from little loligo squid *Uroteuthis chinensis*. J Aquatic Food Prod Technol 24:42–51.

Yanar Y, Celix M. 2006. Seasonal amino acid profiles and mineral contents of green tiger shrimp and speckled shrimp from the Eastern Mediterranean. Food Chem 94:33–6.

Yang S, Zhou Q, Yang L, Xue Y, Xue C. 2015. Effect of thermal processing on astaxanthin and astaxanthin esters in pacific white shrimp *Litopenaeus vannamei*. J Oleo Sci 64:243–53.

Yerlikaya P, Topuz OK, Buyukbenli HA, Gokoglu N. 2013. Fatty acid profiles of different shrimp species: effects of depth of catching. J Aquatic Food Prod Technol 22:290–7.

Zarai Z, Frikha, F, Balti R, Miled N, Gargouri N, Mejdoub N. 2011. Nutrient composition of the marine snail Hexaplex trunculus from the Tunisian Mediterranean coasts. J Sci Food Agric 91:1265–70.

Zhan X, Zheng Q, Fu J, Xu J, Cao J. 2015. A rapid multiplex PCR-DHPLC method of detection and identification of pathogenic bacteria in aquatic products. J Food Saf 35:50–8.

Zhang J, Bhatt TA. 2014. Guidance document on the best practices in food traceability. Compr Rev Food Sci Food Saf 13:1074–103.

Zhang J, Yang X, Kuang D, Shi X, Xiao Y, Zhang G, Gu Z, Xu X, Meng J. 2015. Prevalence of antimicrobial resistance of non-typhoidal Salmonella serovars in retail aquaculture products. Intl J Food Microbiol 210:47–52.

Zheng H, Liu H, Zhang T, Wang S, Sun Z, Liu W, Li Y. 2010. Total carotenoid differences in scallop tissues of Chlamys nobilis (Bivalve: Pectinidae) with regard to gender and shell colour. Food Chem 122:1164–77.

Zhou B, Liu W, Wu Q, Tseng CK. 1991. Application of spirulina mixed feed in the breeding of Bay scallop. Bioresource Technol 38:229–32.

Zimmerman SE. 2016. A compliance guide for selling seafood in the United States. Tom River, N.J.: Urner Barry. p 127.