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REVIEW

Sturgeon, Caviar, and Caviar Substitutes: From Production, Gastronomy, Nutrition, and Quality Change to Trade and Commercial Mimicry

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ABSTRACT
The demand for caviar has increased in recent years because of its high nutritional and commercial values. Consequently, the wild population of sturgeon has decreased. This has shifted the balance of supply of caviar from wild sturgeon to more from farmed fish. The development of aquaculture has resulted in many technical advances of sturgeon rearing. The same factors that encouraged sturgeon farming have also stimulated the search for alternative products optimizing wild-sourced caviar utilization and even created some new market opportunities. Caviar substitutes have been obtained from at least 38 fish species (other than sturgeon) and aquatic animals, e.g., sea urchin, sea cucumber and snails. Although, the emergence of products has not always been positive, as the sturgeon caviar market has been impacted by commercial mimicry, fraud, and mislabeling of caviar-substitutes. This review provides information about the global production and trade of sturgeon, caviar, and caviar substitutes. In addition, the physics, gastronomy, and the quality changes of caviar and caviar substitutes during different fish-harvesting steps are discussed. Moreover, information about commercial mimicry, fraud, and new methods to detect these criminal acts are considered.

KEYWORDS
Sturgeon; caviar substitutes; caviar; *Acipenseridae*

1. Introduction

Caviar is a delicacy consisting of salt-cured roe of the family *Acipenseridae*. The term “caviar” originated from the Persian expression of “Mahi Khaviari,” which means the “egg generating fish” (Bronzi et al. 2011). The most popular and valued caviar has been produced from sturgeon fished in the Caspian Sea. Sturgeon is the common name for 27 fish species belonging to the *Acipenseridae* family. The family of sturgeon has 4 genera namely *Acipenser*, *Huso*, *Pseudoscaphirhynchus*, and *Scaphirhynchus* (Kovalchuk and Hilton 2017; Fahim 2018). The species of this family are mainly distributed in Eurasia and North America and 14 of them are commercially important (Fahim 2018).

The high economic value of sturgeon, mainly because of their caviar, the failure to manage the caviar trade, and unsustainable fishing, along with serious habitat fragmentation have led to a significant decline of wild sturgeon populations (Scarnecchia et al. 2014; Stokesbury et al. 2014; Wu et al. 2019). Since 1997 all sturgeon species have been added to the appendices of the CITES treaty (Convention on the International Trade in Endangered Species) to protect their population from extinction. Consequently, sturgeon aquaculture has developed to cope with the increasing demand and to reduce the pressure on wild sturgeon (Van-Uhm and Siegel 2016; Boscari et al. 2017).

The production of caviar and meat from sturgeon has grown commercially in many countries. Gradually, the mandatory protection of the wild population shifted the production of caviar and sturgeon toward aquaculture. The evolution of sturgeon farming has resulted in the participation of many countries including some with no prior sturgeon industry, representing ∼40% of the aquaculture production (Bronzi et al. 2019). This increase in participation has led to a diversification of caviar products

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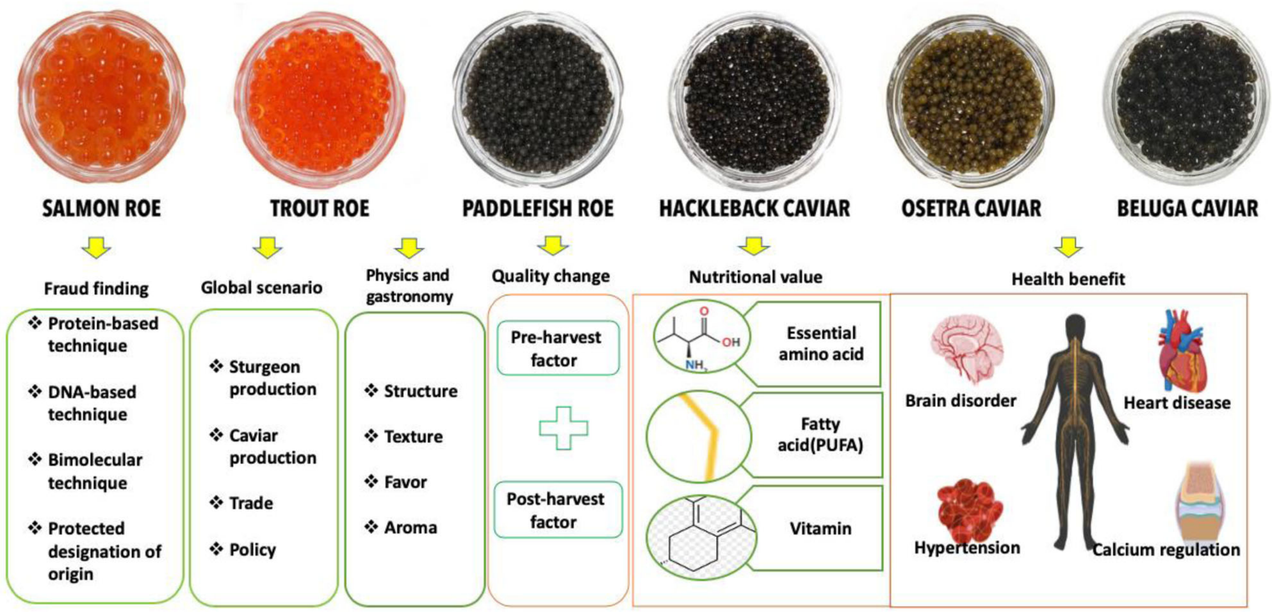

Figure 1. Graphical outline of the different aspects of sturgeon, caviar, and caviar substitutes (The pictures of caviar and caviar substitutes were obtained from a shopping store namely "Caviar Star").

of different quality (Fain et al. 2013; Scarnecchia et al. 2014; Sicuro 2019). Sicuro (2019) has estimated the annual production of caviar will reach between 500 and 2000 tones in the near future.

Other factors driving the demand for caviar from aquaculture species include increased consumer income and the limited accessibility to wild-sourced caviar. The same factors have also drive the market for roe products from fish species other than sturgeon. "Caviar substitutes" is the term that has been considered for the roe products from aquatic animals, shellfish, and fish species other than sturgeon. The term "caviar" must only be used for processed roe from sturgeon according to legislation in a number of countries (Bronzi and Rosenthal 2014). In these countries, the label on the caviar substitute containers often must be noted clearly with the common name of the species of origin. For example, flying fish roe namely "Tobiko" must be labeled as "flying fish caviar." These products often have good nutritional value and health-promoting potential mainly because of their high amount of protein and polyunsaturated fatty acids (PUFA) content (Kocatepe et al. 2012).

The quality of fish roe affects the market value; it differs greatly among species and depends on their feed, harvesting season, habitat condition, processing methods, preservatives, packaging, and storage condition (El-Sheikha and Xu 2017; Ovissipour et al. 2018), which affects their market value. Overall, prices for roe products have been increasing. These products have mostly been pasteurized and frozen after harvesting. Caviar substitutes can be colored or flavored to more closely mimic true caviar along with processing to mimic caviar's sensorial properties, sometimes to the detriment of true caviar. In addition, different names, shapes, and designs for such products have confused or even deceived consumers (Van-Uhm and Siegel 2016; Harris and Shiraishi 2018).

Although, there are several research articles on caviar substitutes, they mostly present information about a single species and may include information about products and markets (Misir et al. 2016; Ovissipour et al. 2018; Bansal and Bansal 2019; Bronzi et al. 2019; Pappalardo et al. 2019). This review will address (1) a global overview of sturgeon production, caviar production, trade and policy; (2) sturgeon caviar and caviar substitutes; (3) nutrition, physics, gastronomy and health benefits of fish roe; (4) factors impacting caviar characteristics and quality; (5) the illegal trade, fraud and commercial mimicry in caviar; and (6) available methods for the identification of fraud. An overall graphical outline of the major topics of the review is shown in Figure 1.

2. Global overview of sturgeon production, caviar production, trade and policy

Since 1997 caviar production from the wild supply of sturgeon has been forbidden or limited by the CITES conservation principles (Heude et al. 2016; Pappalardo et al. 2019). The lack of wild sturgeon provides an opportunity for the marketing of caviars from

Table 1. Fish species known for global caviar production.

Family *Acipenseridae*	General name	Distribution	Commercial caviar	Roe color
Subfamily: *Acipenserinae*				
Genus Acipenser				
Acipenser baerii	Siberian sturgeon	Siberian rivers	Osetra, Caviar d'Aquita, Baerioska	Black
Acipenser brevirostrum	Shortnose sturgeon	North American east coast	Breviro	Black brown, gray
Acipenser dabryanus	Yangtze sturgeon	Yangtze river	Not reported	Not reported
Acipenser fulvescens	Lake sturgeon	Great Lakes, southern Canada	Not reported	Black
Acipenser gueldenstaedtii	Russian sturgeon, Danube sturgeon	Black Sea (rivers: Danube, Denpro), Caspian sea (mainly north parts), Azov sea (rivers: Don, Koban)	Osietra, Almas	Golden, dark gray, olive green, brown
Acipenser naccarii	Adriatic sturgeon	Adriatic Sea and tributaries	Not reported	Not reported
Acipenser nudiventris	Ship sturgeon	Black Sea, Caspian Sea, Azov Sea, Balkhash lake, Rivers: Aral, Volga, Cora	Ship	Grayish black
Acipenser oxyrynchus	Atlantic sturgeon	North American east coasts	Not reported	Black
Acipenser persicus	Persian sturgeon	Caspian Sea (rivers: White, Gorgan, Aral, Volga)	Asetra	Golden, gray, green
Acipenser ruthenus	Sterlet	Black and Caspian tributaries	Sterlet	Mostly golden
Acipenser schrenckii	Amur sturgeon	Amur river	Ossetra, Schrenckii	Gray, golden
Acipenser stellatus	Stellate sturgeon, Derakol	Seas: Caspian (main area), Azov, Black, Aegean	Sevruga	Gray (dark light)
Acipenser sturio	Common sturgeon	Baltic, Atlantic Ocean, Mediterranean, Black	Not reported	Not reported
Acipenser transmontanus	White sturgeon	North American Pacific coast	Amarican, California, Osetra, Calvisius	Golden brown-dark gray
Genus Huso				
Huso dauricus	Kaluga sturgeon	Amur river system	Kaluga	Grayish black
Huso huso	Giant sturgeon	Mediterranean, Black	Beluga	Black, gray
Subfamily: Scaphirhynchina				
Genus Scaphirhynchus				
Scaphirhynchusplatorynchus	Shovelnose sturgeon	Mississippi-Missouri system	Hackleback	Dark gray-black
Family *Polyodontidae*				
Polyodon spatula	Paddle fish	Mississippi river	Spoonbill, American	Grayish black
Psephurus gladius	Chinese paddlefish	Yangtze river system	Not reported	Gray-brown
Hybrids				
A. naccarii × *A. baerii*	AL, Baccarii	Not reported	Not reported	Not reported
A. baerii × *A .gueldenstaedti*	Bagu	Not reported	Not reported	Not reported
A. stellatus × *A. ruthenus*	Schipp	Not reported	Not reported	Not reported
H. huso × *A. ruthenus*	Bester	Not reported	Not reported	Not reported

Information in this table are based on following references: Fain et al. (2013); Pappalardo et al. (2019); Sicuro (2019) Bronzi and Rosenthal (2014); Chen et al. (2016); Monfort (2002); Mims et al. (1999). (Note: caviar harvested from two Polyodontidae and hybrid species are not listed under sturgeons in the Alimentarius Codex).

aquaculture. According to CITES data, until 15 years ago the production of caviar from farmed sturgeon was negligible. At this time almost all caviar is produced from aquaculture-sourced species. Table 1 shows the well-known species of *Acipenceriforms* that are farmed globally for caviar. Caviar harvested from hybrid species and from two species of *Polyodontidae* in the table have not been listed as sturgeon in the Codex Alimentarius (Bronzi and Rosenthal 2014).

Bronzi et al. (2019) have studied sturgeon aquaculture in 46 different countries. They have recorded 2,329 sturgeon farms in 2017, which showed a 7% increase as compared to 2016. The researchers have recorded 25 species of sturgeon being grown. Among them, 4 hybrids and 13 pure species (non-hybrid) were cultured for meat production. The highest percentage of meat production was from *Acipenser baerii* (39.5%), followed by the hybrids of *Huso dauricus* × *Acipenser schrenckii* and *A. baerii* × *A. schrenckii* (35.6%) and *A. schrenckii* (10.2%). According to Bronzi et al. (2019), total harvested sturgeon from all 46 countries was 102,000 tonnes. As shown in Figure 2A, China ranked first in sturgeon production (80,000 tonnes), followed by Russia (6,800 tones), Armenia (6,000 tonnes), Iran (2,500 tonnes), Vietnam (890 tonnes), USA (860 tonnes) and Italy (850 tonnes). The total sturgeon production by the other 39 countries has been reported lower than 850 tonnes each, with a total of approximately 4770 tonnes (Bronzi et al. 2019).

In recent years, due to the growth of sturgeon farming, the global production of caviar has increased (Sicuro 2019). The total production of caviar in 2017 was recorded 364 tonnes (Bronzi et al.

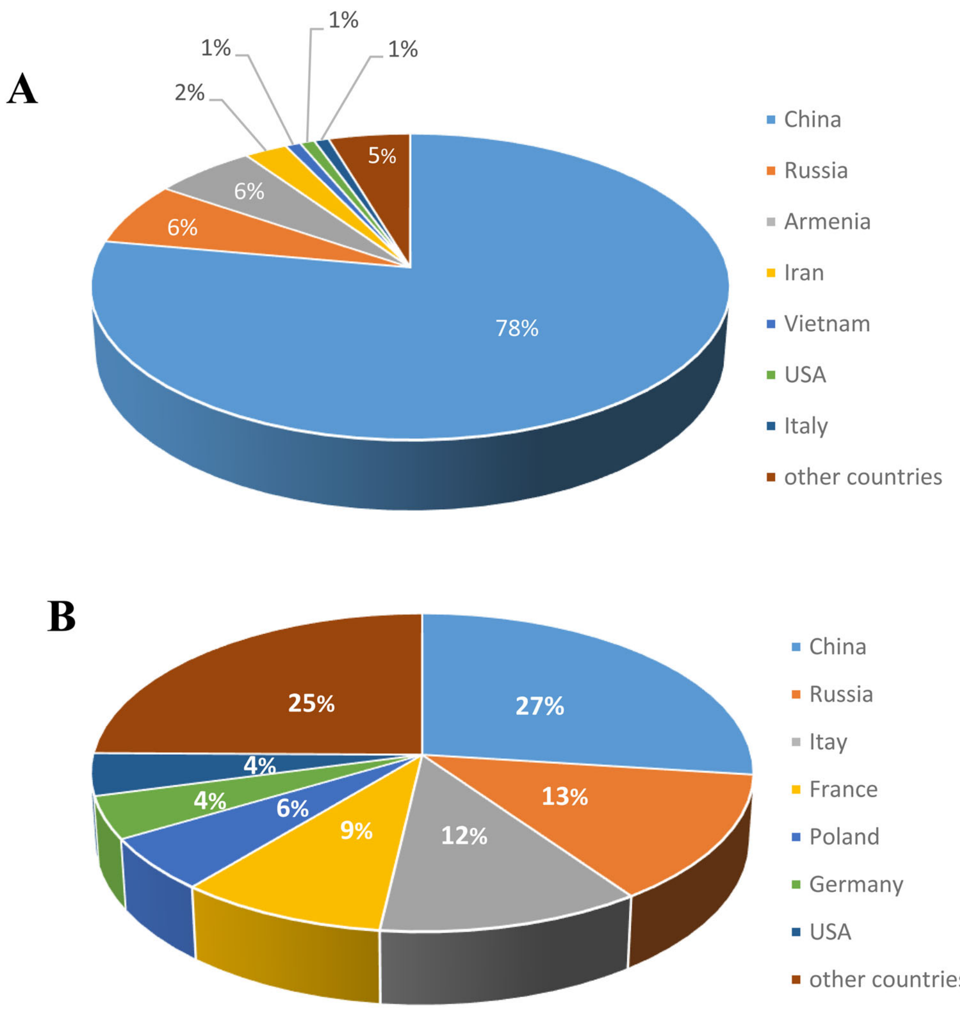

Figure 2. Share of the major countries in sturgeon production (A); Share of the major countries in caviar production (B).

2019). China with 100 tonnes is the biggest caviar producer. After China, the highest caviar production has been reported from Russia (49 tonnes), Italy (43 tonnes), France (37 tonnes), Poland (20.4 tonnes), Germany (16.1 tonnes), and USA (15.9 tonnes). In addition to these countries, ~92 tones of caviar has been produced by 38 countries (each of them lower than 10 tonnes) (Bronzi et al. 2019). The share of the greatest caviar producers is shown in Figure 2B. According to Bronzi et al. (2019), *A. baerii* (31% of the total production), *Acipenser gueldenstaedtii* (20%), *H. dauricus* × *A. schrenckii* (13%) and *Acipenser transmontanus* (12%) were the main caviar species in 2016.

Harris and Shiraishi (2018) reported the global exports of caviar as 1600 tonnes between the years 2000–2015. The portion of aquaculture-sourced caviars in global export was 102 tonnes in 2015. Between the years of 2010–2015, China with a total of 168 tonnes was the number one exporter of caviar, followed by USA (76 tonnes), Italy (51.8 tonnes), France (31.8 tonnes) and Germany (22.7 tonnes) (Harris and Shiraishi 2018). During these years, caviar harvested from aquaculture supplies is considered as the major part of direct exports.

According to the report published by Harris and Shiraishi (2018), 28 member states of the European Union were the first to import caviar with the importing weight of 183 tonnes between the years of 2010 and 2015. The next most common caviar importing countries during these years included the USA with a total importing weight of 93 tones, followed by Japan (79 tones), France (64 tonnes), Germany (54 tonnes), and United Arab Emirates (46 tones). Between 2010 and 2015, three species of wild *Acipenceriforms* namely, American paddlefish (48 tonnes), Russian sturgeon (6.030 tones), and Shovelnose sturgeon (5.416 t) have been the main species in global caviar trade. Moreover, *Acipenser baerii* (98.976 tonnes), the hybrid of *Huso dauricus* × *Acipenser schrenckii* (76.278

Table 2. Main fish and aquatic animal species that have been used to produce caviar substitutes.

Species	Caviar substitute and roe product	Reference
Alaska pollack *(Theragra chalcogramma)*	Mentaiko, Mako, Akko, Kuroko, Iroko	Chen et al. (2016); Bledsoe et al. (2003)
Atlantic cod *(Gadus morhua)*	Tarama, cod roe in a tube, Kaviar with dill	Mexis et al. (2009); Monfort (2002)
Atlantic herring *(Clupea harengus)*	Kazunoko, herring roe on kelp, Kazunoko Kombu, herring roe on shellfish, herring roe with Kamaboko, herring caviar	Bledsoe et al. (2003); Bronzi and Rosenthal (2014)
Pike perch (*Sander lucioperca)*	Galagan	Bronzi and Rosenthal (2014)
Tunas (most of the species)	Bottarga, Poutargue, Karasumi	Bronzi and Rosenthal (2014)
Whitefish *(Coregonus clupeaformis)*	Whitefish caviar, golden whitefish caviar	Bronzi and Rosenthal (2014)
Whitefish Cisco (*Coregonus artedi)*	Cisco, Lojrom, blue fin caviar	Bronzi and Rosenthal (2014)
Mullets *(Mugilidae)*	Bottarga, Poutargue, Karasumi	Bronzi and Rosenthal (2014)
Salmon (many species)	Ikura, Sujiko, Barako, Galagan, salmon caviar	Bledsoe et al. (2010); Bronzi and Rosenthal (2014)
Lump fish *(Cyclopterus lumpus)*	Lump fish caviar	Bronzi and Rosenthal (2014)
Carp *(Cyprinus carpio)*	Taramosalata, Taramas, Tarama	Bronzi and Rosenthal (2014)
Flying fish (*Exocoetidae)*	Tobico, Tobicco, Tobico caviar	Bronzi and Rosenthal (2014)
Trout *(Salmo spp, O. mykiss)*	Trout caviar	Bronzi and Rosenthal (2014)
Sea urchin	Uni, Neri uni, Mizu uni, Doro uni,	Bledsoe et al. (2003)
Sea cucumber *(Stichopus spp)*	Sea cucumber eggs	Bledsoe et al. (2003)
Homarus spp.	Lobster eggs	Bronzi and Rosenthal (2014)
Snail	Snail caviar	Bronzi and Rosenthal (2014)

tonnes), and *Acipenser gueldenstaedtii* (74.785 tones) have been distinguished as the top three aquacultured species in the caviar trade.

Despite all the factors that have reduced the wild supplies of sturgeon, caviar production is expected to increase in the next few years from farmed species. There are many farms in different countries that are being planned and others operating below their planned capacity, which are not yet reflected in production and trade statistics. Therefore, supply may surpass customer demand for both caviar and sturgeon meat sometime in the future. Hence, to balance supply and customer demand, the global caviar market may need to increase customer demand and develop new products to expand usage of this luxury product.

3. Sturgeon caviar and caviar substitutes

3.1. Commercial categories of sturgeon caviar

The commercial categories of sturgeon caviar are described below according to their sensorial properties, size, quality, and price (Moradi 2003; Fain et al. 2013; Chapman and Eenennaam 2019; Sicuro 2019).

Malossol caviar. This type of caviar is a potentially high-quality one with low salt content (2–3%). The captured sturgeon is delivered to the processing plant to be evaluated for the appearance quality and compliance with the standards of quality control. After the quality check, fish are washed to eliminate mucus and surface contamination, and the gills cut to drain blood (2–3 minutes). Then, the abdominal part of the fish is cut open to remove the eggs. Thereafter, the eggs are washed (1–3 times), weighed and salt is added. Since Malossol is known as a light salted caviar, the addition of salt should not be more than 2–3%. Any water being expelled is allowed to drain before the eggs are packed and stored. Products are stored in containers with the temperature maintained at 0–3 °C. This type of caviar can be stored at −2 to −3 °C for three months without preservative and without freezing because of the salt present.

Salted caviar. The processing method for salted caviar is almost the same as for Malossol with the only difference being the higher salt content of salted caviar (10–12% of total weight).

Pressed caviar. Eggs with lower quality and damaged shells have been utilized to produce pressed caviar. Many people have shown more willingness to taste such a product. These are mostly mixed with special colors and have a smoother texture. The processing steps for pressed caviar include soaking the ovaries (eggs still surrounded by membranes) in saturated brine at 24 °C to increase the firmness of the eggs; separating roe and washing; soaking the eggs in saturated brine for 1.5–5 minutes at 38–45 °C with a ratio of 1:5 (w/v) caviar: saturated warm brine; draining excess water; and pressing the eggs.

Ovulated egg (no-kill caviar). The processing of Malossol, salted, and pressed caviar are known as traditional methods, but "ovulated egg" has recently been introduced as a new processing method for caviar production. In this method, the female sturgeon usually receive a hormone or labor is induced artificially to release their eggs without killing or even cutting the fish open. In the next step, the eggshells of treated eggs are modified and protected from swelling and water-hardening. Ovulated eggs also need to be

Table 3. Proximate main chemical compositions of caviar and other fish roe (g/100 g roe).

Fish/roe	Crude protein	Lipid	Moisture	Ash	Carbohy-drate	Energy (KJ/100 g)	Reference
Beluga	24.7	15.9	48.4	4.1	6.9	1330	Mol and Turan (2008)
Sevruga	24.2	14.7	51.5	4.2	5.4	1240	Mol and Turan (2008)
Osetra	24.0	14.6	52.0	4.8	4.6	1220	Mol and Turan (2008)
Chum salmon	27–35	12–20	50–56	1.5–1.7	–	–	Bledsoe et al. (2003)
Pink salmon	23–38	10–15	50–60	1.9–2.0	–	–	Bledsoe et al. (2003)
Sockeye salmon	20–29	10–13	56–58	0.7–1.7	–	–	Bledsoe et al. (2003)
Chinook salmon	21–34	8–18	51–70	1.2–1.9	–	–	Bledsoe et al. (2003)
Labeo rohita	70.2 (%N × 6.25)	20.2	66.9	3.8	–	–	Rao et al. (2010)
Channa striatus	58.8 (%N × 6.25)	22.7	48.5	5.12	–	–	Rao et al. (2010)
Skipjack tuna	20.4	1.9	75.3	1.1	–	–	Yoon et al. (2018)
Whiting roe	7.35–14.5	0.38–9.71	76.09–83.99	0.86–1.49	1.14–2.77	64–154	Galla et al. (2012)
Rainbow trout	26.5	7.74	61	1.96	–	187	Machado et al. (2016)
Lota lota	16.2	9.4	64.5	1.4	–	–	V'uorela et al. (1979)
Burbot	13.2	6.8	77.7	0.6	–	–	V'uorela et al. (1979)
Blue fish	19.2	9.3	70.1	–	–	–	Iwasaki and Harada (1985)
Sea bream	20.3	4.9	73.4	–	–	–	Iwasaki and Harada (1985)
Sardine	24.4	6.0	68.7	–	–	–	Iwasaki and Harada (1985)
Smelt, Shishamo	24.1	13.2	61.4	–	–	–	Iwasaki and Harada (1985)
Angler fish	11.5	5.3	82.1	–	–	–	Iwasaki and Harada (1985)
Squid	23.4	5.1	70.0	–	–	–	Iwasaki and Harada (1985)
Crab	30.2	13.0	55.4	–	–	–	Iwasaki and Harada (1985)

(-): not reported.

prevented during processing from forming a jelly coat. This type of caviar is known as no-kill caviar in some countries.

3.2. Caviar substitutes

Fish roes, nutritionally rich products, are considered as luxury foods (Hoseinifar et al. 2016). Roe from fish species other than sturgeon have often been removed and discarded (Klomklao et al. 2014). More of these products are being processed and sold because of their quality, palatability, nutrition value, and their beneficial effects on human health (Galla et al. 2012; Chen et al. 2016). These products have been more readily available and accepted by consumers because of their high protein content, as well as unsaturated fatty acids, especially eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Monfort 2002; Saliu et al. 2017; Stefánsson 2017).

"Caviar substitutes" is the name for the processed fish roe from species other than sturgeon. Global markets for these types of products are expanding. These products can be flavored and colored to somewhat match true caviar in sensorial attributes (Bledsoe et al. 2003). The production of caviar substitutes with a variety of species has been estimated to be up to 50,000 tonnes (Sicuro 2019). These products have been derived from more than 38 non-sturgeon fish species (Pappalardo et al. 2019). The list of well-known fish and other aquatic animals, which have been used for the production of caviar substitutes and their products are shown in Table 2. Other products and categories relevant to the caviar substitutes and their relationship with true caviar will be discussed in the section on fraud and mimicry.

4. Nutrition, physics, gastronomy and health benefits

4.1. Nutritional composition and potential health benefits of fish roe

Because of the good nutritional attributes, fish roe has been well studied (Chalamaiah et al. 2013; Binsi et al. 2017; Bekhit et al. 2018; Caredda et al. 2018). The nutritional composition of caviar and caviar substitutes are significantly different among species. This is because of the maturity of the eggs, as well as the geographic area, harvesting season, and the method of processing. With the increase of the maturity level, the mass and ratio of water to lipids will be increased. After the brining procedure, the moisture content will be decreased, and the percentage of protein and lipid content will be increased (Bledsoe et al. 2003).

Table 3 shows the nutritional composition of various fish roes. Generally, fish roe contains 72–74% water, 18–20% crude protein, 3–6% lipid, and up to 1–2% minerals (Bledsoe et al. 2003). For different fish species, the composition of the fatty acids in these products are significantly different. They contain different amounts of the medium-chained, saturated fatty acids which are of concern to the most beneficial essential fatty acids, i.e., those that cannot be synthesized directly by the human body and have to be obtained from food. Table 4A shows the average fatty acid composition of fish roe as recently reported by

Table 4. The average fatty acid spectrum of fish roe (A); main off-flavors related to caviar (B); the most important odor-active compounds in caviar and caviar substitutes (C).

Fatty acid	Average content (%)	Fatty acid	Average content (%)	Fatty acid	Average content (%)
C 14:0	1.7	C 18:2 n-7	2.0	C 20:3 n-6	0.1
C 15:0	0.8	C 18:2 n-6	1.0	C 20:4 n-6	2.2
C 15:1	0.6	C 18:3 n-3	0.6	C 20:5 n-3 EPA	4.0
C 16:0	20.0	18:3 n-6	0.3	C 22:4 n-6	0.3
C 16:1 n-7	4.0	C 18:4 n-3	0.5	C 22:5 n-3	1.0
C 17:1	1.7	C 20:0	0.25	C 22:5 n-6	1.7
C 18:0	6.5	C 20:1 n-9	0.3	C 22:6 n-3 DHA	24.0
C 18:1 n-9	20.0	C 20:2 n-6	0.1		

Off-flavor	Chemical compounds	Species
Muddy, earthy	Geosmin	*Lates calcarifer*
Muddy	Geosmin and isoborneol	*Oncorhynchus mykiss, Ictalurus punctatus, Oreochromis niloticus*
Earthy and musty	Geosmin and isoborneol	*Oncorhynchus mykiss*
Fishy	Aldehydes	*Acipenser transmontanus*
Acipenser transmontanus	Geosmin and isoborneol	*Micropterus salmoides, Acipenser transmontanus*
Boiled potato-like	Strecker aldehydes	*Gadus morhua*
Earthy, musty, woody, fishy, rancid, rotten, petroleum	Geosmin and isoborneol	*Salmo salar, Cyprinus carpio, Ictalurus punctatus, Oreochromis niloticus, O. aureus*
Musty	Isoborneol	*Ictalurus punctatus*

Odor-active compound	Olfactory characteristic	Origin
(E,Z)-2,4-Decadienal	Green, roasted, fatty, fishlike	Fatty acid
(E,Z)-2,6-Nonadienal	Green, cucumber-like, melon-like	Fatty acid
(E,E)-2,4-Decadienal	Green, fatty, chicken skin-like, broth like	Fatty acid
2-Nonenal	Green, waxy, greasy, melon-like	Fatty acid
Nonanal	Green, floral, waxy, citrus peel-like	Fatty acid
(Z)-4-Heptanal	Green, oily, milky, creamy, cheesy	Fatty acid
Methional	Sulfuric, fermented, cheesy, matured, cooked	Amino acid
Octanal	Green, waxy, z citrus peel-like, fishy	Fatty acid
Hexanal	Green, fatty, leave-like	Fatty acid
1-Octen-3-ol	Green, mushroom-like, musty	Fatty acid
2-Pentylfurane	Carame-like, fruity, green, earthy	Sugar
Phenylacetaldehyde	Aromatic honey-like, honigartig, spicy, sweet, floral	Amino acid

Information in part A and C are from the article by Vilgis (2020), and part B from the article by Sicuro (2019).

Vilgis (2020). The high proportion of essential n-3-fatty acids, i.e., DHA and EPA is particularly important. The potential of DHA and EPA in the treatment of coronary heart disease, neurodegenerative, and neurological disorders has been reported (Dyall 2015; Harris et al. 2017).

Protein is another main component of caviar and fish roe. In general, fish roe has an average of 75% ovoglobulins, 13% collagen, and 11% albumin. Fish roe also contains lysozyme, which is a strong antibacterial agent (Vilgis 2020). Gong et al. (2013), showed that the crude protein content of caviar samples ranged from 24.0 to 25.6% of wet weight. Glutamic acid (actually a mixture of glutamine and glutamic acid due to analytical issues) has been identified as the most abundant amino acid (7.29–7.69%). Mol and Turan (2008) identified the glutamic acid, aspartic acid (also aspartame and aspartic acid), lysine, and serine as the major amino acids in Beluga, Sevruga, and Osetra caviar.

Caviar and caviar substitutes are also rich in minerals, especially calcium, iron, magnesium, manganese, phosphorus, potassium, copper, and zinc. These products also have a high level of vitamins, especially vitamin D3 or cholecalciferol. This is due to the feeding of fish on various plankton species, which contain large amounts of pre-vitamin D2 and D3.

4.2. Physics and the gastronomy of caviar and caviar substitutes

Traditionally, only sensorial parameters have been used to evaluate the quality of caviar and fish roe. Apart from sensorial methods, physical methods can also be used. Fish roe is similar to poultry eggs (Bledsoe et al. 2003). Figure 3 shows the general structure of fish roe. As shown in the figure, proteins and oil droplets are stored in a soft shell, which is composed of a flexible layer of connective tissue. The egg white is found under the collagen layer and toward the central part of the egg. The yolk can be observed; separated by another protein layer, the so-called vitellin membrane (Vilgis 2020).

The perceptions of consumers of the physical aspects of consuming caviar and caviar substitutes have varied. In general, their description has mainly

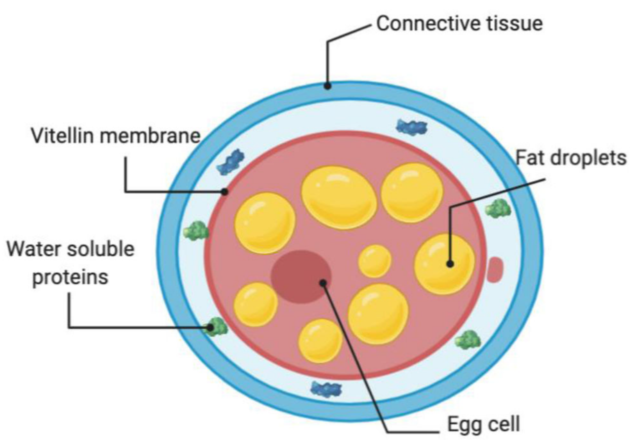

Figure 3. General structure of fish roe. The central part (light-brown) containing egg cell and oil droplets which known as "yolk"; and the blue part which containing water-soluble proteins known as "white" in all fish eggs.

focused on the special smooth solid skin of the roe when it is burst under the teeth force during chewing and the aromatic agents released in the mouth. Vilgis (2020) has described this procedure as the "explosion-test," which is an important culinary sensation when evaluating caviar. The same researcher has also done a study on the mechanical explosion of sturgeon caviar and rainbow trout roe. This study has shown that large parts of the physicochemical sensations of caviar and caviar substitutes were associated with the physical aspects of texture. The author concluded that the dissolved free amino acids in the aqueous phase of the eggs contribute to generating the umami taste, and the bitter-sweet and slightly sour flavor of the eggs.

Taste and flavor are two major characteristics for quality evaluation of the caviar and caviar substitutes. The taste is strongly affected by the processing methods. The amount of salt also has an important role in the taste. Moreover, free glutamic acid, which has an "umami taste" may be the most prevalent amino acid in fish roe. Additionally, the flavor compounds identified in several PUFA are also reported as the main origins of the aroma in caviar and fish roe (Vilgis 2020).

5. Factors impacting caviar characteristics and quality

Traditionally, caviar and fish roe were graded based on the uniformity of their size and/or sensorial characteristics. This pattern has been changing and caviar quality is described according to other factors, such as ovarian fat content as well as the presence of off-flavors (Lu and Rasco 2014). Shin et al. (2010) reported that caviar quality differs greatly among species. They have stated that the quality of caviar depends on the vitellogenesis, follicular atresia, season, ovarian fat content and the level of maturity. Lu and Rasco (2014) have reported that the lipid and protein contents of sturgeon roe significantly depended on the level of maturity. The females of *Acipenser transmontanus* were found to be mature after 6–8 years in aquacultural systems. Additionally, vitellogenesis in this species started in the fall and the final gonadal maturation happened during the late spring or early summer in the second year. Moreover, follicular atresia significantly reduced the yield and negatively affected the firmness, flavor, taste, shelf life, and marketability of the fish roe. To improve the roe quality, yield, and economic value of caviar production, it is necessary to identify mature fish during the sturgeon farming period to prevent ovarian follicular atresia. Currently, two useful methods include "ultrasonic scanning based on the measurement of calcium concentration in sturgeon blood plasma" and "plasma concentration of vitellogenin and sexual steroids" have been suggested by Delwiche et al. (2016) and Lu and Rasco (2014).

A number of methods has been developed and applied to assess the quality and flavor of fish roe and caviar, to increase the acceptability to customers (Lourenço et al. 2019; Sicuro 2019). Customers' demand for caviar mainly depends on the roe size, natural color, and the level of color blur. Roe with big size and pale color is the most popular and attractive to consumers. Texture and flavor are the next two important parameters in caviar acceptability (Sicuro 2019). The habitat condition, maturity level, and processing methods can significantly affect the composition and quality of caviar (Shin et al. 2010; Fajkowska et al. 2019). Hence, the factors affecting the quality changes of caviar and fish roe can be clustered into two main categories: pre-harvesting and post-harvesting conditions of the fish.

5.1. Quality change of caviar before fish-harvesting: the effect of habitat condition, diet and maturity level

Several studies have attempted to determine the agents that cause off-flavor in fishery products (Li et al. 2015; Hong et al. 2017; Tavakoli et al. 2018). Schrader and Rimando (2003) reported a total of 300 volatile compounds in fish roe and other seafood products. Lipophilic compounds have been identified as the main reason for sensorial change and off-flavor in caviar and caviar substitutes (Sicuro 2019). Aldehydes, geosmin, and isoborneol have been identified as water-borne off-flavor agents for caviar, fish roe, and other fishery products. These components have been found on aquaculture farms and in fish habitats. Fish can take up these compounds through their skin, gills, and mouth during feeding or water consumption. The fish may accidentally ingest some of the microorganisms producing these compounds during feeding. These microorganisms can directly or indirectly affect the quality of caviar and caviar substitutes (Schrader and Rimando 2003).

Sicuro (2019) described the major substances that are the leading causes of various types of off-flavor in caviar (Table 4B). These compounds have caused fishy odor, musty, earthy, woody, rancid, petroleum, and rotten flavor in caviar and other fishery products. In general, these changes have been generated as a result of microbial contamination. Another sensory study of caviar and other fishery products showed two strong odorous metabolites: geosmin [trans-1,10,-dimethyl-iratfs-(9)-decalol] and 2-methylisoborneol (exo-l,2,7,7-tetramethyl- [2.2.1]heptan-2-ol). Geosminis produced mainly by planktonic cyanobacteria (blue-green algae) and the 2-methylisoborneol by *Streptomyces* spp. (the most important species of *Actinomycetes*). Geosmin and 2-methylisoborneol result in earthy and musty odors, respectively. Additionally, β-cyclocitral that originates from eukaryotic algae, has been identified as a main cause of woody and tobacco odors. It has been shown that off-flavor-generating species of planktonic cyanobacteria are the main cause of this unusual odor in fishery products (Schrader and Rimando 2003).

5.2. Quality change of caviar after fish-harvesting

5.2.1. The effect of processing methods

Handling and the techniques that are used for caviar and/or caviar substitute production could affect the product quality (Sicuro 2019). Fresh roe from fish is microbiologically sterile. Although, the eggs do not remain sterile when they are separated and enter the screening and processing lines. Total volatile nitrogen bases (TVBN), histamine, and other biogenic amines are mostly generated by bacteria, such as *Pseudomonas* sp. and coliforms, and adversely affect the quality of fish roe and caviar (Sicuro 2019). Bledsoe et al. (2003) showed that 38% of Sevruga caviar samples and about 57% of Osetra samples were contaminated with *Aeromonas* sp., *Proteus* sp., and *Vibrio* sp. Al-Holy et al. (2004) have also reported that *Listeria monocytogenes* and *Clostridium spp.* can negatively affect caviar and fishery products.

The processing and storage condition of caviar must be optimal. Otherwise, bacteria will grow and increase the volatile nitrogen bases, peroxides, free fatty acids, ammonia, and biogenic amines of caviar. These compounds can result in many inappropriate organoleptic changes. Additionally, the unsaturated fatty acid content of caviar and fish roe are relatively unstable, and can easily take part in oxidative chain reactions. These reactions can generate undesirable aromatic compounds as well as fatty, waxy, and green odors. These olfactory attributes have mostly originated from the fat degradation compounds and some others from sugar and protein fragmentation. A universal classification of these aliphatic aroma compounds with their origins and olfactory characteristics is shown in Table 4C, as described by Vilgis (2020).

Recently, "HACCP" (i.e., best practices) and "nuclear magnetic resonance spectroscopy (NMR)" (i.e., chemical detection of compounds of interest) have been suggested by Sicuro (2019) as efficient techniques to control the contamination and spoilage of caviar. The preservation methods for caviar production mostly included adding additives (such as antimicrobial and antioxidant agents and flavor enhancers) and pasteurization. These preservatives can significantly affect the quality of caviar.

5.2.2. Additives and preservatives

Sodium chloride (NaCl) at 2–6% has been reported as the only globally accepted additive, preservative, and flavor enhancer of caviar (Moradi 2003; Shin et al. 2010; Sicuro 2019). Also, cold temperature of 4 °C has been considered as the main method for the short-term storage of caviar (Sicuro 2019). For long-term storage of caviar, it has been suggested that the temperature should range between −1 to −4 °C to enhance the stability up to 24 months. These temperatures have also been suggested by Ovissipour et al. (2018) as the best conditions for storing caviar at home and in restaurants.

In European countries, boric acid and sodium borate with a maximum concentration of 4 g/kg can legally be added. Sodium tetraborate decahydrate (borax) in caviar can increase the Millard reaction. In Iranian sturgeon caviar, borax with a maximum concentration of 4 g/kg is used (Rizzi 2007). Safari and Yousefi (2010) used a mixture of sodium chloride, boric acid, and borax to control the growth of *Clostridium botulinum* in caviar. The mixture of sodium chloride and methylparaben has also been used to control the bacterial contamination of caviar (Sicuro 2019).

Table 5. Preservative methods and components employed and suggested in caviar and caviar-like products.

Preservative	Country	Roe/caviar	Reference
Pasteurization	General	All caviar and fish roe	Ovissipour et al. (2013)
Tetraborate decahydrate (borax)	General	Iranian caviar	Safari and Yousefi (2010)
NaCl	General	All fish roe	Shin et al. (2010)
Refrigerator (–1 to –4 °C for long time storage)	General	All fish roe	Ovissipour et al. (2018)
Refrigerator temperature (4 °C)	General	All fish roe	Sicuro (2019)
Vacuum-packaged, pasteurization at 50 70 °C	General	White sturgeon	Al-Holy and Rasco (2006)
NaCl (5%) + boric acid (0.3%) + borax (0.4)	General	Persian sturgeon	Bledsoe et al. (2003)
High pressure	General	Siberian sturgeon	Sicuro (2019)
Natural preservatives	General	Carp	Binsi et al. (2019)
Different type of plastic packaging + pasteurization	General	Salmon	Ovissipour et al. (2018)
Electric field pulse (PEF) + high pressure	General	Lumpfish, salmon	Gudmundsson and Hafsteinsson (2001)
1-Borax (0.3%) + boracic acid (0.1%) 2-Boraxn (0.3%) +urotropine (0.1%) 3- Potassium nitrate (<0.16%) 4-Sorbic acid (<0.1%) +urotropine (0.1%) 5-Urotropine (<0.2%) + tripolyphosphate (0.15%) 6- Urotropine (<0.1%) + sodium benzoate (<0.1%)	Russia	Sturgeon caviar	Bledsoe et al. (2003)
Sodium benzoate (<0.1%)	General	Sturgeon caviar	Bledsoe et al. (2003)
Benzoate (≤0.05%)	France	Sturgeon caviar	Bledsoe et al. (2003)
Formic acid (<0.05%)	Switzerland	Sturgeon caviar	Bledsoe et al. (2003)
Sodium or potassium nitrate (<0.012%) + erythorbic acid (<0.025%) + nicotinamic (<0.018%) + polyphosphate (<0.045%)	Japan	Salmon roe (sujiko)	Bledsoe et al. (2003)
Potassium nitrate <0.16%)	General	Dry cured roe products of carp, whitefish, pollack, herring	Bledsoe et al. (2003)
Potassium nitrate (200 ppm)	USA	Cod	Bledsoe et al. (2003)
Sodium benzoate (1000 ppm) + potassium sorbate (1,000 ppm) + (3.5% brine solution)	Iceland	Green sea urchin roe (uni)	Stefánsson and Olafsdottir (2017)

Water bath pasteurization of glass jars is a promising technique for caviar preservation. The technique allows for less stringent handling temperatures which has made it possible to use by cruise lines and airlines. Therefore, pasteurization can enhance the palatability of caviar and decrease the amount of salt used (Ovissipour et al. 2013). Fish roe is not heat resistant and the temperature used should not be higher than 70 °C. Higher temperatures would lead to protein denaturation (Al-Holy and Rasco 2006). Various methods for caviar preservation are summarized in Table 5. These methods are used although the physical treatments are not as widely used because of some negative effects observed on the sensorial attributes of caviar and caviar substitutes.

6. Illegal trade, fraud and product mimicry

6.1. Illegal trade

Since 1990, the Caspian Sea, as the largest supply of sturgeon species has been the site of much of the illegal caviar trafficking. With increasing global market demand for black caviar, this trend grew until the identification of an extinction risk for Caspian sturgeon. As the wild supply of Caspian sturgeon was prohibited to prevent extinction, the traffickers targeted North American habitats of sturgeon as an alternative (Zabyelina 2014). Overfishing and the illegal trade along with habitat destruction and river fragmentation (mainly by damming) have led to a major reduction in the natural supply of sturgeon. Since 1997 sturgeon species have been put into the appendixes of the CITES regulations. CITES is the main international agreement with specific rules about wildlife trade. The agreement includes Appendix I (trade from species under a high level of extinction risk that have been prohibited from fishing) and Appendix II (controlled-trade from some specific species that have partially been permitted) (Doukakis et al. 2012). Sturgeon have also been listed by the IUCN (International Union for Conservation of

Nature) as species with an extinction risk (Boscari et al. 2017).

Any trade of sturgeon and paddlefish, and their derivatives (meat, roe, caviar) must be issued and permitted by the pertinent national management and the authorities at CITES. Possessing sturgeon caviar to a maximum of 125 g/person does not need the CITES authorities' permission. All containers of sturgeon products must have the following information on their label: the production and expiration date, the source of the product (wild or aquaculture) and the country of origin. Even with the recent exception (125 g/person), full and genuine CITES labeling is required (Jahrl 2013).

Despite these restrictive treaties, there is still a considerable illegal trade of sturgeon and caviar from unsustainable wild sources. The main reasons for the illegal trade are the high price of caviar, the long-term investment needed to produce caviar from farmed sturgeon, the low supply of wild sturgeon, and the rapid rise of aquaculture-sourced sturgeon and caviar with diverse grades (that then lead to manipulation of the lower grades to appear as a higher grade). It has been estimated that the share of caviar in the illegal trade has exceeded, by approximately ten times the legal trade (Boscari et al. 2017; Harris and Shiraishi 2018). Harris and Shiraishi (2018) have categorized different types of caviar trafficking as summarized below:

1. Trafficking either meat or caviar of sturgeon from the wild supply to gain financial profit through online markets, individual contacts, or other legal and illegal open-air markets.
2. Trading caviar without CITES label or labeled with incomplete information.
3. Changing the label of caviar harvested from wild-sourced species with those harvested from aquaculture sources to sell through the legal trade chain.
4. Labeling the aquaculture-sourced caviar as the wild-sourced or those aquaculture-source caviar with a higher quality level to gain a monetary advantage.
5. Receiving trade permission illegally (mostly using forged CITES certificates, or obtaining genuine documents using corrupt methods).

According to Harris and Shiraishi (2018), illegal trade significantly decreased the numbers of wild sturgeon. To solve this problem, legal authorities such as CITES, should enact more effective regulation and rules about the trade of sturgeon and caviar. In addition, there must be a balance between caviar supply and customer demand. Then, the pressure on wild sturgeon supply may be reduced.

6.2. Fraud, commercial mimicry and mislabeling

Recent specific food market information has introduced the idea of "fraud and mimicry" as a global challenge. These often will be classified as "transnational organized crime," which has come about in part because cooperation of well-equipped traffickers with financially-corrupt law enforcers (Van-Uhm and Siegel 2016). Traffickers cheat customers with illegal distribution of products in markets to gain high monetary profits and this is the "fraud." This illegal behavior is mostly associated with misbranding, mimicry, mislabeling, and geographic copying. The European Parliament in 2013 and Interpol Europol (part of the global police network) in 2016 have, respectively, designated fishery products as the second and third most important food products with a risk of fraud. This classification was based on a comprehensive market study in 57 different countries (FAO 2018).

Caviar is the most valuable and luxury fishery product. Sicuro (2019) estimated the value of the global food luxury market in 2016 was between 46 to76 billion Euros. Caviar has always been a high risk for fraud and mimicry with caviar substitutes, especially in the context of sensorial features (Bronzi and Rosenthal 2014). Mimicry has appeared as a competitive marketing strategy. It has led producers to develop new marketing strategies to increase customer's trust and a willingness to purchase their products. From this point of view, caviar substitutes have been promising as an effective marketing strategy for imitation caviar products. In 2011, the global production of these products was estimated at more than 50,000 metric tonnes. They have significantly different shapes, quality, recipes, ingredients, labels, and so on (Bronzi and Rosenthal 2014). These products have mostly sold for less than 250 USD/kg. Based both on price and production, these large amounts of caviar substitutes can act as strong competitors with caviar in the global market.

Caviar substitute products sometimes contain no fish roe. They can contain fish or crustacean meat, seaweed, microalgae, and vegetables. Labels on these products must specifically show information about the species, eggs, dates, etc. In some cases, the label has been changed to mislead the customers. Deliberately mimicking the design of a brand and the commercial names of caviar substitutes in a special way to imply the image of true caviar is another misleading behavior. The term "caviar" on the label of caviar substitutes are used as a marketing strategy to imply inaccessible luxury or high-quality products that are associated with the emotional image beyond its use as a more regular food product (Bronzi and Rosenthal 2014). Bronzi and Rosenthal (2014) have listed the main categories of caviar and caviar substitute in global markets:

- *Caviar*: Have been produced only from sturgeon roe.
- *Derivatives*: Products that contain some true caviar as a marketing strategy. Such products have targeted the customers who may not be a regular caviar consumer, but the image and beauty of the real products are important to them.
- *Substitutes*: These products have been made of eggs from snails, sea urchins, and fish species other than sturgeon. Substitutes have mostly been colored and flavored with different substances to better match the appearance of real caviar.
- *Imitations*: They have been produced from numerous products, e.g., fish meat, seaweed, and some biological materials; these products imitate the true caviar in taste and sometimes in appearance.
- *Emotional*: The term "caviar" on the label of such types of products has been used only as a marketing method to simulate luxury expectations. While these products not only contain no true caviar, they are also sometimes non-edible.
- *Simulations*: Have been produced from fish and some other biological substances with the objective of imitating the taste of true caviar.

In addition to these products, several other commercial mimicries of true caviar have been found in global markets based on their ingredients. These products include caviar-like substances that were herring/anchovy meat-based, non-herring/anchovy products, Lobsviar, Onuga, seaweed-based, Cavianne and soy caviar (Bronzi and Rosenthal 2014; Sicuro 2019).

The improvement of the global caviar market in the future would strongly benefit from a harmonized international labeling system, which currently does not exist. As discussed above, legal globally recognized organizations such as FAO and CITES have emphasized that only processed roe from sturgeon should be labeled as caviar. Roe from species other than sturgeon should be labeled as caviar substitutes. Recently, China has been the only country that has strongly followed the CITES labeling agreement to open up their market globally (Wei et al. 2011).

Since 2006, to implement the CITES labeling requirements, the European Union (EU) has enacted a regulation that requires mandatory caviar labeling for all the Union members. These regulations have obligated all EU members to attach a detailed and non-reusable CITES label on all sturgeon caviar containers. All caviar containers with any color and size, from wild stocks or farms, hybrid or genuine, domestic or international export or import must be labeled according to the regulation (Jahrl 2013). According to the EU agreement, the label of each caviar container must present the following information:

1. Standard species code

Each sturgeon species has a specific code. This code has been extracted from the first three capital letters of their specific name. For example, the standard code of *Acipencer persicus* has been defined as *PER*, or the standard code for *Acipencer sinensis* has been defined as *SIN*.

2. Supply code

"W" stands for caviar harvested from wild-sourced sturgeon; "C" stands for the caviar harvested from aquaculture-sourced sturgeon; "F" stands for the caviar harvested from a sturgeon grown on a farm with one or two wild parents.

3. Code of origin country

This code has a two letter ISO (International Standards Organization) code, e.g., China would be XX, Iran would be YY and the USA would be ZZ.

4. The year that the caviar had been harvested
5. Official code of the caviar processing center.

Each country which exports caviar must establish a registration system to record the code of official processing centers.

6. Batch identification number

6.3. Fraud identification of caviar

To identify caviar species, it is necessary to use advanced analytical methods. Using the identification techniques is more important when processing changes the morphological features of the fish species and/or their products (Pappalardo et al. 2017). Several protein-based techniques such as electrophoretic analysis, high-performance liquid chromatography, and enzyme-linked immunoassay have been used to identify different fish species. Since cooking operations mostly lead to protein denaturation, the protein-based methods can normally only be used for raw products (Hsieh et al. 2010).

The modern biomolecular techniques can be promising for fraud identification in fishery products (Bénard et al. 2015; Pappalardo et al. 2019). DNA-based techniques have been developed to identify the origin of caviar when morphological properties cannot be used. These are cost-effective, fast and compatible with a wide range of samples (Bénard et al. 2015). Among the DNA-based techniques, the DNA-barcoding method has been used to identify more than 98% of fish and other animal species by targeting the sequence diversity in about 650 base pairs (bp) of the mitochondrial cytochrome oxidase I (COI) gene (Pappalardo et al. 2015; Vitale et al. 2015; Christiansen et al. 2018; Conti et al. 2019).

The polymerase chain reaction-restriction fragment length polymorphism (PCR-RFLP) method is another efficient and cost-effective method that has been used to identify fish species (Chen et al. 2014). Although, PCR-RFLP of the cytochrome b gene has some limitation when it comes to recognizing several closely-related sturgeon species such as *Acipencer gueldenstaedti*, *Acipencer baerii*, *Acipencer persicus,* and *Acipencer naccarii* (Ludwig 2008). Cytochrome oxidase I barcode-restriction fragment length polymorphism (COIBar-RFLP) is another efficient molecular approach that has successfully been used for the identification of caviar and other seafood products (Pappalardo et al. 2019). Protected designation of origin (PDO) requirements also has been used in Sweden to identify fraud in roe products of *Coregonus albula* (Sicuro 2019).

7. Conclusions and future perspectives

Caviar and caviar substitutes have recently increased in popularity in international markets. The health-promoting and nutritional value of these products has been shown. The potential of increasing caviar consumption and market trends in the future will be based on caviar production (mainly by aquaculture), customer demand, and the pricing system. The future trade of sturgeon and caviar is promising since sturgeon farms and consumer markets are rapidly expanding globally. If the production of caviar continues to follow the current trend, caviar supply may surpass consumer demand. A high rate of caviar production along with diversification of the available sources of true caviar as well as expansion and improvement of caviar substitutes may decrease the price and allow greater access to this traditional luxury market for caviar. In this case, caviar will not be as unique as it was in the past. By decreasing the price, medium-income consumers may become caviar customers. Hopefully, these new customers will be well informed about "what is true caviar and what are caviar substitutes?", so that the products they purchase will meet their expectations with respect to both quality and safety. If done properly, more consumers will become long term caviar and caviar substitute customers.

Recently, many researchers have shown that the conditions of the habitat and/or farm, feeding, maturity level, processing method, preservatives, and storage affect the quality of caviar and caviar substitutes. It seems that caviars harvested from aquaculture are more available and easier to have consistent handling and processing conditions over time than the wild supplies. In addition aquaculture permits: (1) responsibility and control of feed and water usage, along with accountability: (2) the use of hormone and antibiotic treatments can be minimized or prohibited with fish for human consumption; (3) and, hopefully, aquaculture may take off much of the pressure on the endangered wild sturgeons. The industry would also benefit from enforcement of labeling requirements both within a country and with international trade, better traceability of products, and a more honest and lower pricing system. The use of cost-effective and fast analytical techniques to identify the origin of caviar and to avoid fraud and mimicry needs to be an accepted part of the marketing system. Hopefully, this will create a long-term successful sturgeon caviar and caviar substitutes industry.

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