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Review

Eating Sturgeon: An Endangered Delicacy

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Abstract: Since ancient times, sturgeon species have been valued for their rich nutritional qualities, which are crucial for human health today. They are linked with gastronomic delicacy and offer economic benefits, especially for the caviar industry. Today aquaculture produces more farmed and hybrid species due to rapidly declining wild sturgeon populations. Sturgeon diversification through processing can yield fingerlings, stocking material, meat or caviar. Because of its variety, sturgeon flesh includes highly digestible proteins, lipids, vitamins and minerals. Consuming sturgeon provides essential fatty acids that play important oxidative and anti-inflammatory roles in human cells. The purpose of this study is to examine the sustainability and economic value of eating sturgeon worldwide, the technology applied in food processing, and the challenges that food quality and authenticity, nutritional content and health effects pose. The issue of counterfeiting high-quality sturgeon products by dishonest means has to be adequately addressed. Digital tools to guarantee authenticity and transparency in the sturgeon value chain should be considered in the future.

Keywords: food quality; sustainability; food security; sturgeon; authenticity; food technology; nutritional profile; health; caviar

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1. Introduction

In the commercial sector, the population of a valuable fish known as sturgeon (Acipenseridae family) (Figure 1) is rapidly declining as a result of several circumstances. They include altered river streams, the development of hydropower plants, illicit fishing, and other detrimental human activities [1]. The International Union for Conservation of Nature reports that sturgeons are a fish category believed to be on the verge of extinction [2]. Compared to other threatened animal breeds, Acipenseriformes have the highest percentage of severely endangered species. A new aquaculture subfield called commercial sturgeon farming was created given the dramatic decline in the number of native sturgeon inhabitants [3,4]. This occurred when the demand for caviar expanded in recent years due to its outstanding nutritional profile and commercial potential. Sturgeons have become less common in the wild as a result. As a consequence, more caviar is now coming from farmed fish instead of wild sturgeon [5].

The elemental fish composition may vary depending on a number of factors, such as species, nutritional status, season and body size, among others [6]. The vitamins such as niacin, pyridoxine, vitamin B12, essential amino acids and minerals like potassium, magnesium and phosphorus in sturgeon are some of its constituents. Sturgeon meat has an amazing taste because it contains glutamic acid (18.1%) [7]. Two long-chain omega-3 fatty acids present in sturgeon flesh are docosahexaenoic acid (DHA) (3.8–11.1%) and eicosapentaenoic acid (EPA) (4.9–6.8%) [8]. Heart disease, poor cognition, depression, cancer, arthritis and a whole range of other health complications, are linked with omega-3 deficiency. Given sturgeon's high unsaturated fatty acids content, fish products are crucial for human health. Therefore, eating sturgeon positively impacts skin regeneration, metabolism, blood pressure, among other factors. As sturgeon is quickly digested and is low-calorie, but maintains high energy values, it is regarded as dietary [9].

Figure 1. *Acipenser ruthenus.* This pure freshwater sturgeon species is native to the Pontocaspian region. Sturgeon presents a unique external appearance and traits.

Sturgeon biomass generation has grown in the past 10 years, with 102.327 tons worldwide by 2017, according to Bronzi et al. [10]. In China, sturgeon production was 79.6 tons in 2017, which represents 78% of the world series as a consequence of fish hunting. Furthermore, 6.6% of world production (around 6.8 tons) comes from Russia. Given their quick adaptability to many farming methods and oxygen tolerance, sturgeon species present a global growth trend. Thanks to their exceptional qualities, including the ease with which they adapt to farming settings and their valuable caviar and thick flesh, these species are potential aquaculture prospects [11]. Since the 1990s, several publications have discussed sturgeon and caviar production and trade trends around the world [1,12–15].

In line with these premises, this review aims to examine the economic relevance and sustainability of consuming sturgeon worldwide, the food processing technologies involved in its production, food quality and authenticity issues, and its health impacts and nutritional profile.

2. Sustainability and Economic Relevance

Sturgeons with twenty-five species are one of the oldest existing fish and are believed to be one of the most endangered vertebrate groups worldwide with more than 85% of species classified as threatened or endangered [16]. The sturgeon farming industry has increased because the caviar market demand is on the rise [5,17]. The main species that are used in aquaculture production include the Siberian sturgeon (*Acipenser baerii*), Russian sturgeon (*Acipenser gueldenstaedtii*) and White sturgeon (*Acipenser transmontanus*). Others include Beluga sturgeon (*Huso huso*), Sterlet sturgeon (*Acipenser ruthenus*), Persian sturgeon (*Acipenser persicus*), Stellate sturgeon (*Acipenser stellatus*) and some hybrids [15,17]. The highest quality sturgeon meat is obtained from White sturgeon (*A. transmontanus*) while the most renowned and valuable caviars are named Beluga, from *H. huso*, Osetra, from *A. gueldenstaedtii*, and Sevruga, from *A. stellatus* and *A. persicus* [17].

Globally and precipitously declining populations have been closely associated with overharvesting and loss of habitats in relation to river functionality alterations [18]. Lots of countries are involved in harvesting caviar from sturgeons for it to be exported. China is the number one caviar exporter with 168 tons, followed by the USA (76 tons), Italy (51.8 tons), France (31.8 tons) and Germany (22.7 tons) [19]. The same authors also report that 28 EU Member States were the first to import caviar with imports of 183 tons between 2010 and 2015. The next commonest caviar-importing countries for the same period were the USA, which imported 93 tons, followed by Japan (79 tons), France (64 tons), Germany (54 tons) and United Arab Emirates (46 tons). For the 2010–2015 period, three wild Acipenceriforms species, namely American paddlefish or spoonbill (48 tons), Russian sturgeon (6,030 tons) and Shovelnose sturgeon (5416 tons), have dominated the global caviar trade [17].

As the global sturgeon market has grown, its harvesting is unsustainable, and impacts on the sturgeon population are devastating. With the biggest sturgeon species supply, since 1990 the Caspian Sea has been a site of considerable illegal caviar trafficking [19]. This trend has increased because the global market demand for black caviar is rising. Wild Caspian sturgeon supply was forbidden to avoid its extinction. Thus, traffickers have sought alternatives and targeted North American sturgeon habitats [20]. Sustainability issues are related to illegal trade, overfishing, habitat destruction and river fragmentation (mostly by damming), which have markedly reduced natural sturgeon supplies.

White Sturgeon is also related to food security and plays an essential role in connecting and maintaining people to natural systems. For instance, sturgeon can be caught all year long in the Fraser River and its tributaries by indigenous people in Canada [21]. A commonplace practice is to share big smoked/salted fish and meat with families in the community, especially elders [21,22]. The eggs of sturgeon females are boiled and eaten, and other fish parts (i.e., brains and insides of backbones) are removed for medicinal purposes [23]. Value addition to the sturgeon fisheries in these communities can help to expand opportunities for local business operators to reach the global market, improve their purchasing power and promote food security. Sturgeon can also serve as a valuable ingredient in the cosmetics industry. Caviar extract including docosahexaenoic acid (DHA) has a biological role in regulating adiponectin production in adipocytes and can act as a skin anti-aging agent in UV-irradiated fibroblasts [24]. In many parts of the world however, which include Canada, indigenous people are excluded and adversely influenced by natural resource management and approaches to species that favor settler values and usage.

Biocultural diversity is increasingly recognized as a relevant conceptual framework for communicating interrelations between the diversity of cultures and ecosystems. Indigenous people, whose well-being, economies and cultures are extremely interconnected with the biophysical world, can significantly contribute to sustainability discussion [25].

The world's aquaculture sturgeon production has been estimated at 120,000 tons of sturgeon meat and 700 tons of caviar [26]. Given recent advances in sturgeon aquaculture and ever-growing luxury consumers, there is a vast potential to reshape caviar consumption. The market is so lucrative that it accounted for €217–253 billion in 2016, which is roughly 1.5 times the world aquaculture production. Top quality Beluga caviar (*Huso huso*) was sold at retail prices of €10,000 per kg, while the caviar of commonly farmed species may be sold for prices around 10% of this amount. with retail prices are presently reaching levels up to €2000 per kg for White sturgeon (*A. transmontanus*) in Italy [13].

Sturgeon's high economic value, mostly because of its caviar, failure to manage caviar trade and unsustainable fishing practices, including serious habitat fragmentation, have resulted in significantly declining wild sturgeon populations [27–29]. This is further exacerbated by late maturity in sturgeon, over-harvesting and loss of habitat. In order to protect the sturgeon population from extinction, all its species have been included in the Convention on International Trade in Endangered Species Treaty appendices since 1997. Sturgeon aquaculture is more compelling than for other fishes due to the unusually long time to harvest eggs from sturgeon (usually 7–10 years), and the depletion of the wild natural form of the fish due to human activities and overharvesting for caviar has made some species to be extinct or on the verge of extinction. This has allowed sturgeon aquaculture to develop in order to cope with rising demand and to lower the pressure placed on wild sturgeon [5,10,30,31].

3. Processing and Preservation Technologies

Sturgeon fish consists of a complex combination of proteins, fats, carbohydrates, water, minerals, and vitamin compounds that can be easily spoilt resulting in waste through the action of undesirable microbes if not well processed or preserved [11,32]). Caviar deteriorates fast since freezing temperature is not permitted and food additives are also prohibited [13]. The storage temperature ranges from (+2 °C to +4 °C) during packaging in retail while for wholesale business the temperature range is set between 0 °C and 4 °C [13].

Consequently, to preserve the quality of the sturgeon and extend its shelf-life during storage, appropriate processing and preservation techniques must be employed for sturgeon meat and caviar.

As the sturgeon population is declining, measures to ensure its availability for longer periods will include both thermal and non-thermal processing technologies to help commercial sturgeon farming. In this section, we highlight the processing of two main products from sturgeon meat and caviar.

3.1. Sturgeon Meat or Flesh

As the sturgeon flesh shelf life is short, it can be preserved by reducing its water activity with freezing, but the quality deteriorates upon thawing. This involves identifying a method that not only maintains sturgeon quality but also extends it, which would be very significant for the sturgeon industry [33]. The current state of processing and preservation technologies, with implications on sturgeon flesh quality and shelf life, has been reviewed by many authors such as [11,34–36].

Thermal processing methods, such as boiling, steaming, microwaving or baking, which impact sturgeon meat flavor, have been investigated by sensory analysis and instrumental techniques [37]. Similar effects have been reported in cooked European sea bass and how it affects consumer preferences [38].

A sturgeon photodynamic non-thermal disinfection preservation technique mediated by curcumin (PDT) has successfully prolonged sturgeon shelf life with positive effects on sturgeon quality [39]. The cited authors followed this technique by combining an LED light source, inexpensive curcumin and low-cost disinfection [39]. Surgeon liver tends to be wasted but can be extracted by three-phase partitioning [40]. According to these authors, the quality of both the obtained protein and oil conferred high nutritional value, with a very high value for further industrial application.

Compared to traditional sturgeon meat cooking, the digestion properties of sturgeon myofibrillar protein treated by low-temperature vacuum heat at distinct processing temperatures (50 °C, 60 °C, 70 °C) and for differing times (15 min and 30 min) can relieve protein conformation heat stress [40]. The authors concluded that this reduced protein aggregation and, thus, improved protein accessibility to digestive protease, and also increased digestibility [41]. The low-temperature vacuum heating with tea polyphenol-processed sturgeon fillets combination markedly lowered the free arginine concentration and increased the free amino loss rate. Both inhibited the generation of advanced glycation end products [42]. This was possible because tea polyphenol competed with glucose to bind to free arginine [42]. Nevertheless, very little research has been conducted into the factors that influence quality changes (sensory and texture) in superchilled sturgeon fillets.

The effects of cathepsin function, protein oxidation and several freezing temperatures on sensory and texture attributes during superchilling storage have been investigated by Zhao and et al. [33]. The obtained results revealed that the ice crystals that formed at several freezing temperatures crucially impacted the texture and muscle structure indicators. Hence these results can inform about superchilling practices when storing sturgeon fillets. These findings can further inform about the development of other preservation methods. One example is irradiation combined with superchilling to prolong sturgeon fillet shelf life.

Applying *sous vide* pretreatment to cooking sturgeon burgers resulted in improved sensory and physico-chemical properties [43]. These authors confirmed that *sous vide* can effectively inhibit off-flavors from oxidation and prevent evaporative losses of flavor volatiles (aromatic compounds, nitrogen oxides and organic sulfur) while cooking [43].

The farming of sturgeon, its processing resulting in products for the market in Western Europe as reviewed by Williot and co-authors [44] are shown in Figure 2 below.

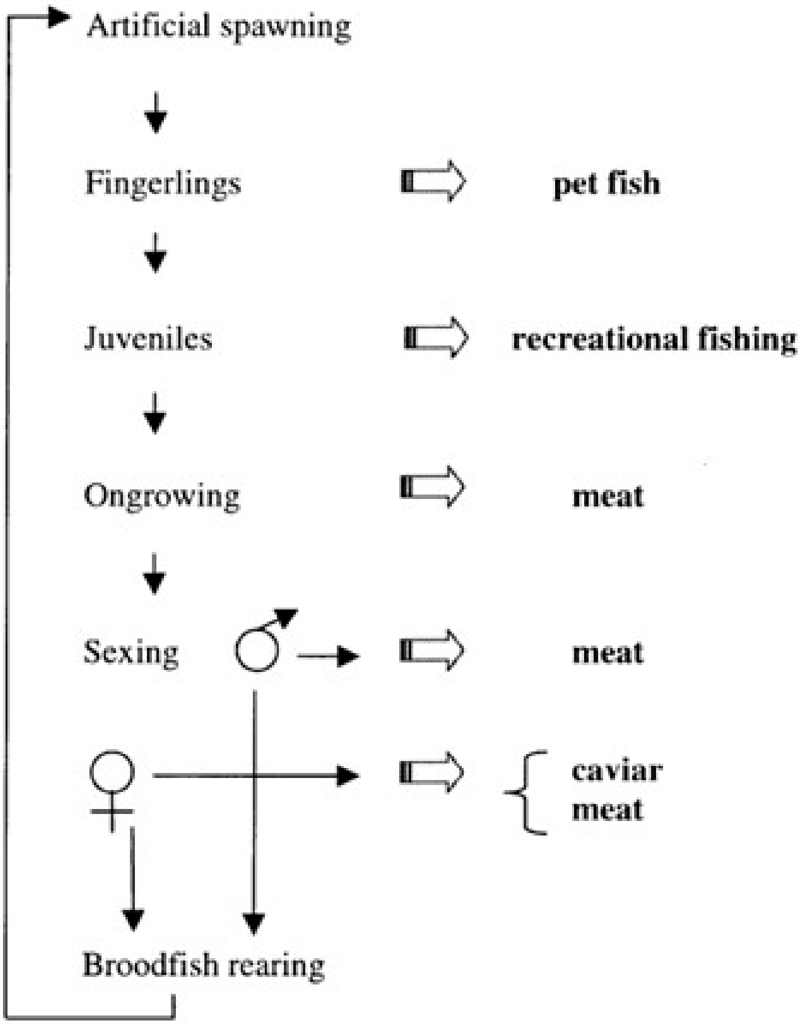

Figure 2. The chief sturgeon-related production steps and marketing products in western Europe. Source: adapted from ref. [44].

3.2. Sturgeon Caviar or Eggs

Caviar is produced mainly from sturgeon roe. However, to cover global demand, different fish species (mullet, salmon, carp, etc.) have been introduced on caviar markets, which warrants the need for authenticity. Fish type, caviar condition (e.g., location maturity and harvest time) are some of the most relevant factors that can affect chemical fish caviar composition [45]. Traditionally processed caviar, malossol, may not be adequate to supply demand, and this has led to some processing variants to increase supply by flash pasteurization or pasteurization. Other attempts include developing caviar from salmon roe or rainbow trout [43,46]. Caviar quality depends primarily on the quality of its raw material, and spoilage can be due to several factors. For instance, the physical, chemical and microbiological changes that take place during storage and account for differences in product quality [46].

Commercial caviar growing and harvesting are now popular owing to overfishing in the wild. Sturgeon is globally raised to produce caviar by means of aquaculture. The flow diagram in Figure 3 depicts the processing of caviar from the sturgeon. The process is described in the Food Technology magazine published by the Institute of Food Technology, USA, as documented by McHugh below in 2020 [47].

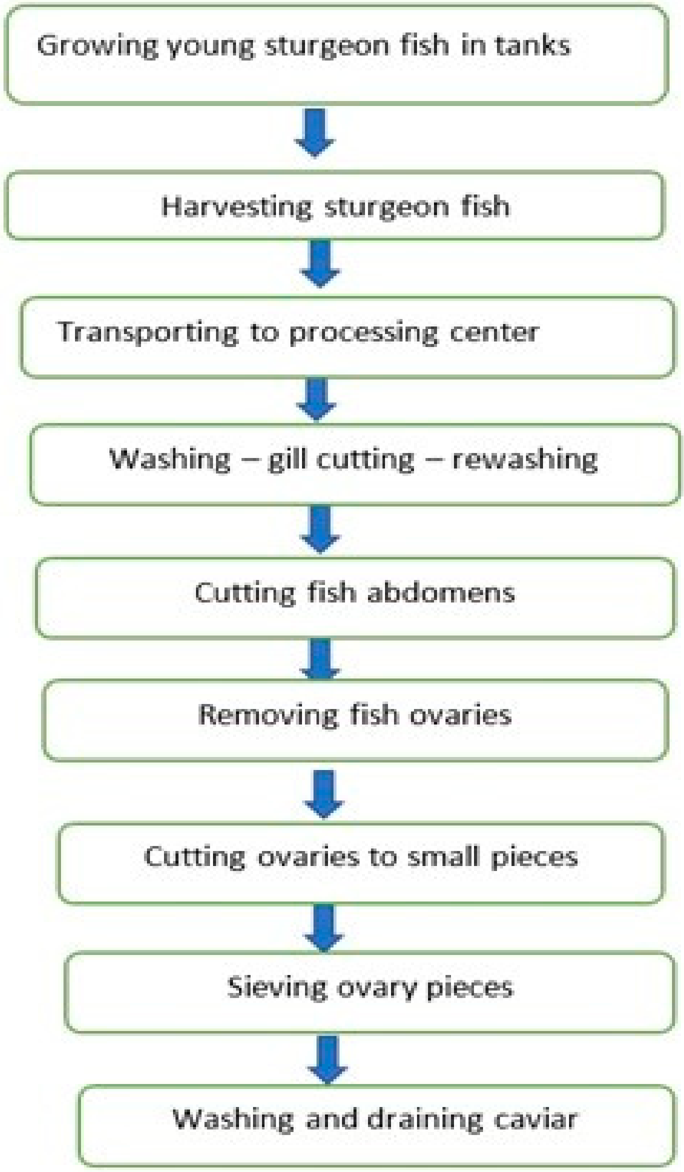

Figure 3. Flow diagram for the growing and harvesting of caviar from sturgeon. Source: adapted from ref. [48].

Young sturgeons are grown in tanks before harvesting. It can take 7 to 10 years for fish to be harvested for eggs. Eggs account for 15–18% of sturgeon weight. Fish are purged in clean water tanks in the next processing step to remove off-flavors. They are then rapidly stunned—for the sturgeon fish to lose consciousness quickly either by electric shock or response to carbon dioxide stunning method is applied. Afterward, both ovaries are removed by the so-called "stripping" process, which extracts caviar by making a small incision in the fish wall. An alternative is to extract caviar by Cesarean section and then stitching up so that females continue to produce roe. The third roe removal process is performed by massaging eggs out of fish. Fragile eggs are chilled and carefully hand-removed from membranes by rubbing eggs against a mesh screen. Then the tissue is removed for composting purposes.

Eggs are repeatedly rinsed in cold water to wash away impurities, any broken eggs, and also membrane residue. Then caviar is weighed and salted. Most high-quality caviar contains <3% salt, and lightly salted (5%) caviar is known as malossol. Caviar with up to 8% salt content is called salted caviar or semipreserved caviar, and its flavor is less fresh. The product name is payusnaya if more than 10% salt is added. It forms a jelly-like cake that can be stored for up to three months. For caviar packaging, lacquer-lined tins are normally employed, hand-filled and gently pressed to remove air. Tins are tightly sealed to avoid oxidation. Caviar is left for three months to age. Aging is critical for end product flavor and, typically, fresh caviar can be stored for 2–4 weeks. Freezing and drying can contribute to prolonging caviar shelf life. Pasteurization can also prolong its shelf life and enables storage times for up to 1 year at room temperature [47].

4. Food Quality and Authenticity

Proteins, lipids, carbohydrates, water, minerals and vitamin components make up the complex collection of organic molecules that constitute sturgeon tissue. These compounds are quickly decomposed by digestive enzymes or fermented by microorganisms [49]. As a result of all this, fish lose their nutritional value during storage, which renders them unfit for ingestion and potentially develops hazardous properties. The development of bacteria may be to blame for spoiling the sturgeon [32]. Therefore, several methods, such as refrigeration, frosting, freezing [50,51], vacuum packaging and modified atmosphere packaging [52], as well as enzyme inactivation using natural compounds like plant solution rich in natural antioxidants, smoking, salting, among others, have been followed to preserve sturgeon quality and prolong its shelf life [53,54].

Traditional methods can be followed to evaluate sturgeon species. Assessments of lipid oxidation products, including thiobarbituric acid reactive substances (TBARS), total volatile basic nitrogen (TVB-N) and peroxide value (PV), are some frequently applied physico-chemical assays that act as markers of fish freshness [55]. The sensory attributes of raw and cooked fish muscle are made by human perception; e.g., taste, texture, color, odor and flavor [56].

Most physico-chemical, sensory and microbiological approaches are regarded as being rather expensive, long-lasting and time-consuming despite them all being used to assess the authenticity and quality of fish and fish products. Recently, attention has been paid to examining non-destructive and non-invasive instrumental approaches, including infrared and fluorescence spectroscopy techniques. These procedures may even be completed by staff with very little training because they are quick, reasonably affordable and environmentally friendly. They provide plenty of information based on a single test. Additionally, not many samples of preicosapentanoic acidration are required for spectroscopic methods, and in certain circumstances, no preicosapentanoic acidration is required at all [57]. The fraudulent practices that imitate authentic sturgeon meat and caviar products with counterfeits in this lucrative business is worrisome [1]. It is important that consumers get value for their money and the need for better quality and authenticity will require fast and cost-effective analytical techniques. The present study discusses in detail the use of the most recent untargeted methods to determine sturgeon quality and authenticity.

Untargeted techniques, such as spectroscopy methods, are beneficial for being quick, inexpensive and mostly destructive-free. Procedures have proven effective in identifying the authenticity and quality of fish [58–60], dairy products [61–64], eggs [65–67] and other foods.

4.1. Fluorescence Spectroscopy

Despite the popularity of this method, relatively few research works have looked at how fluorescence spectroscopy can be applied to assess sturgeon quality. Numerous fluorophores can be found in sturgeon in small amounts. They include aromatic amino acids and nucleic acids (AAA + NA), vitamins A, tryptophan, riboflavin and nicotinamide adenine dinucleotide (NADH), and many more substances. On this matter, Boughattas et al. [68] recently tracked the degree of Russian sturgeon (*Acipenser gueldenstaedtii*) freshness while stored at 4 °C. Having set excitation at 340 and 380 nm, the emission spectra of NADH (360–600 nm) and riboflavin (405–650 nm) were respectively recorded from sturgeon slices. Riboflavin spectra have a maximum fluorescence intensity range that goes from 460 to 490 nm and varies with storage duration. The observed peak was attributed to a variety of stable fluorescent oxidation products, such as those produced when unsaturated aldehydes react with proteins and/or with the photo breakdown of riboflavin products. Several peaks with wavelengths of 380, 460 and 485 nm were revealed for NADH spectra. Scientists concluded that the degree of freshness of sturgeon samples was connected to the form of NADH spectra. Particularly during storage, the fluorescence intensity of sturgeon samples both decreased (at 460 and 485 nm) and increased (at 380 nm). Scientists attributed a sharp drop in fluorescence intensity between 460 and 485 nm to NADH oxidation. This occurred during sturgeon storage and converted NADH into NAD+, which changed the structure of the NADH fluorescence spectra. Their research led to several important discoveries. One such discovery was that NADH spectra can be used as fingerprints to establish the degree of sturgeon freshness. The conclusion was validated because four groups (2 days, 5, 6 and 7 days, 8 and 9 days and 12 days) were found after applying common components and specific weights analysis to the data tables of both riboflavin and NADH. Another fluorophore, AAA + NA, was utilized to keep track of Russian sturgeon during cold storage. After setting the excitation wavelength at 250 nm, emission spectra AAA + NA were captured from 290 to 400 nm [68]. The authors not only noticed that the highest emission value was around 375 nm, but the shape of spectra changed depending on how long samples were stored. The 12-day-old sturgeons had maximum fluorescence intensity, while that of the 2-day-old ones was minimum. Differences in protein-water, protein-protein and/or protein-lipid interactions could account for this variation. When looking at the vitamin A spectra, the shape of spectra revealed a maximum of 296 nm for the 2-day-old sturgeons and of 310 nm for the older ones. Researchers attributed this red shift to the following factors: (i) the physical states of triglycerides in fat globules; (ii) fat globule membrane-protein network interactions (iii) lipid-lipid interactions.

As emphasized by recent regulatory actions, fish authentication is crucial for accurate product labeling [69]. Fluorescence spectroscopy has been employed in this situation to assess freeze-thaw cycle effects (1, 2, 3, 4) on the quality of Russian sturgeon (*Acipenser gueldenstaedtii*) stored in partial vacuum and total vacuum. The NADH emission spectra of the sturgeon samples that had been submitted to several freeze-thaw cycles showed two peaks at 388 nm and 470 nm. Fresh samples' maximum fluorescence intensity was recorded at 388 nm, with the highest fluorescence intensity at 470 nm for the samples that had undergone four freeze-thaw cycles while stored in a partial vacuum [70]. Fresh samples, the samples that underwent one freeze-thaw cycle and those stored in partial vacuum and total vacuum all revealed the maximum fluorescence intensity at 296 nm for vitamin A in their spectra. Additionally, a red shift was noted in the maximum excitation spectra of vitamin A (from 296 nm for the samples stored in a total vacuum and partial vacuum after one freeze-thaw cycle and at 306 nm for the samples in 2, 3 and 4 freeze-thaw cycles). The riboflavin spectra of sturgeon samples presented two peaks at 468 nm and 500 nm. Alterations of <500 nm were caused by the degradation of riboflavin or its interactions with other substances like proteins. The compounds created by unsaturated aldehydes reacting with proteins can be used to measure the degree of fish oxidation with the spectral range between 405 and 480 nm [57]. The authors independently performed the PCA on each intrinsic probe to acquire information from datasets. The best outcomes were for the vitamin A and riboflavin spectra [70]. In fact, it was possible to distinguish between the fresh sturgeon samples and those that had only undergone one freeze-thaw cycle. A distinction was also made between the samples that had been subjected to 2, 3 and 4 freeze-thaw cycles.

4.2. Mid-Infrared Spectroscopy

One established technique for characterizing the structural properties of proteins and peptides is mid-infrared (MIR) spectroscopy. This approach was applied by Jiang and Rui-Zhang Guan [71] to characterize sturgeon in this context. According to their findings, absorption at 1376 (–COO-), 1344 (–COOH, –C-O), 1310 (–COOH, –C-O), 1157 (C-O-C, C-O-H, C-O), 883 (C-H) and 856 (OSO_3, C-O-S) cm^{-1} was revealed for sturgeon samples. Sturgeon chondroitin sulfates include 4 6-disulfated chondroitin sulfates.

A recent study by Noman et al. [72] employed MIR spectroscopy to assess the quality of Chinese sturgeon (*Acipenser sinensis*). The spectra of lyophilized protein hydrolysate samples were scanned within the 4000–500 cm^{-1} range. These authors established absorbance in Amide regions with protein hydrolysate samples that appeared at 1626 cm^{-1} (Amide I), 1511 cm^{-1} (Amide II) and 1388 cm^{-1} (Amide III) for the papain hydrolysate sample. The absorbance regions of alcalase hydrolysate samples occurred at 1626 cm^{-1} (Amide I), 1518 cm^{-1} (Amide II, and 1388 cm^{-1} (Amide III). The release of the peptides and free amino acids of complex protein-rich substrates depends on raw sturgeon quality and the employed enzymes.

By a different approach, whether MIR could distinguish between fresh Russian sturgeon samples and those undergoing one, two, three or four freeze-thaw cycles was examined [70]. Three wavenumber regions (3000–2800 cm^{-1}, 1700–1500 cm^{-1}, 1500–900 cm^{-1}) held most of the spectral data. Absorbance bands 1083, 1118, 1158, 1239, 1314, 1371, 1396 and 1418 cm^{-1} appeared in the 1500–900 cm^{-1} spectral area. Two peaks (1371 and 1418 cm^{-1}) were found in the fresh sturgeon samples, but they vanished in the samples submitted to freeze-thaw cycles. Both the C-H bending of alkenes and the O-H bending of the C-O-H group could have contributed to the peak at 1418 cm^{-1}. The 1000–1200 cm^{-1} spectral area distinguished very well between the fresh samples and those having undergone four freeze-thaw cycles during storage in partial and total vacuums. There were two peaks at 1547 and 1637 cm^{-1} in the area between 1700 and 1500 cm^{-1}. According to Pinilla et al. [73], the Amide I band (1600–1700 cm^{-1}) was the most feasible spectral area to determine the secondary structure of proteins. Protein underwent oxidation throughout the freeze-thaw cycle of sturgeon samples. This resulted in a variety of α-helix, β-sheet, β-turn and random coil levels, which respectively exhibited an absorption band in the 1650–1660 cm^{-1}, 1600–1640 cm^{-1}, 1660–1690 cm^{-1} and 1640–1650 cm^{-1} spectral areas. Both a decrease in α -helix, β-sheet and random coil and an increase in β-turn were seen in the secondary structure %. The β-turn increased from 35.40% for the fresh samples to 39.70% and 37.06% for the samples subjected to the four freeze-thaw cycles and stored in a partial vacuum and a total vacuum, respectively). The α-helix decreased from 10.70% for the fresh samples to 9.30% and 9.23% for the samples subjected to four freeze-thaw cycles stored in partial vacuum and total vacuum, respectively) [70].

The C-H bond of the methylene and methyl groups of fatty acids appeared in the area between 3000 and 2800 cm^{-1}. For the fresh samples, this spectral area revealed two bands at 2852 and 2925 cm^{-1}, which vanished throughout the freeze-thaw cycles. This reveals that MIR spectroscopy can be used to promptly detect commercial fraud cases in the fish industry and to overcome several authentication issues [70].

5. Nutritional Profile and Health Impacts

Some health and nutritional benefits are associated with eating sturgeon meat, eggs or caviar. The proximate composition of three species of sturgeon meat (Siberian *A. baerii*, Russian *A. gueldenstaedtii* and White *A. transmontanus*) has been analyzed by Lopez et al. and matched those of previous studies by other authors with *A. baerii* and *A. transmontanus* muscle [17,74,75]. The total protein content analyzed by the Kjeldahl method was higher in female White Sturgeon meat (19.6%) than in male White Sturgeon meat (18.6%) and female

Siberian Sturgeon meat (17.6%). Total lipid contents fell within the 2.6% range in White Sturgeon and 5.6% in Siberian Sturgeon [17]. As described by Stansby [76], sturgeon meat can, therefore, be classified as a medium-fat high-protein product, which makes it an appealing food with good market potential. This is because sturgeon meat contains limited fat content of high nutritional value, particularly essential fatty acids [17]. Siberian Sturgeon's medium-fat meat is considered suitable for certain processing techniques like canning and smoking, which normally result in consumers appreciating the product more [77].

In the work by Lopez et al. [17], for fatty acids in sturgeon meat, unsaturated fatty acids prevailed compared to saturated fatty acids in all the samples. However, some differences appeared in the groups, especially for the meat obtained from male White Sturgeon, which seemed enriched in polyunsaturated fatty acids (PUFA) (44.2%) compared to the meat from female sturgeons of the same species used for caviar production (33.9%), and those obtained from lightweight caviar-designated Siberian Sturgeon females (35.2%). An overview of the results obtained from not only proximate composition but also from the fatty acid composition of the fillet meat samples taken from different sturgeon species is found in Tables 1 and 2.

Table 1. Proximate composition (g/100 g) of the fillet meat samples from different sturgeon species and size. Data are mean ± standard deviation.

Sturgeon Species	**Siberian (*A. baerii*)**	**White (*A. transmontanus*)**	**White (*A. transmontanus*)**
Farmed for	Caviar production	Caviar production	Meat production
Gender	Female	Female	Male
Average fish weight	5–8 kg	30–50 kg	6–10 kg
n	5	5	5
Proximate composition			
Moisture	75.5 ± 1.6	75.2 ± 3.3	77.7 ± 1.1
Ash	1.3 ± 0.2	1.2 ± 0.3	1.1 ± 0.0
Lipid	5.6 ± 1.7	3.9 ± 2.5	2.6 ± 0.8
Protein	17.6 ± 0.5 ^{A}	19.6 ± 0.8 ^{B}	18.6 ± 0.5 ^{A,B} **

^{A,B} = values in the same row with a different letter are significantly different ** = $p < 0.01$.

Table 2. Fatty acid composition (g/100 g of fatty acids) of different sturgeon species fillets. Data are mean ± standard deviation.

Fatty Acid (g/100 g)				**Sign.**
14:0	1.3 ± 0.1	1.9 ± 0.6	1.7 ± 1.3	
16:0	15.5 ± 0.7	17.6 ± 0.8	16.9 ± 1.9	
18:0	2.4 ± 0.5 ^{A}	3.9 ± 1.4 ^{A}	5.9 ± 1.2 ^{B}	**
ΣSFA	19.2 ± 0.6 ^{A}	23.4 ± 1.6 ^{B}	24.5 ± 3.3 ^{B}	**
16:1n7	3.3 ± 0.6	3.4 ± 1.1	2.9 ± 2.0	
18:1n9	37.5 ± 2.6 ^{A}	34.0 ± 2.3 ^{A}	25.0 ± 6.3 ^{B}	**
18:1n7	2.8 ± 0.1	3.1 ± 0.1	2.9 ± 0.3	
20:1n9	1.8 ± 0.1 ^{A}	2.2 ± 0.5 ^{A}	0.5 ± 1.1 ^{B}	**
ΣMUFA	45.5 ± 2.8 ^{A}	42.7 ± 3.5 ^{A}	31.3 ± 5.5 ^{B}	**
18:2n6	16.1 ± 0.3	11.9 ± 0.7	14.1 ± 5.1	
18:3n6	1.3 ± 0.4 ^{A}	0.4 ± 0.1 ^{B}	0.4 ± 0.2 ^{B}	**
18:3n3	2.7 ± 0.4 ^{A}	1.6 ± 0.4 ^{B}	1.9 ± 0.8 ^{A,B}	*
20:2n6	0.9 ± 0.2	0.7 ± 0.2	0.8 ± 0.3	
20:3n6	0.5 ± 0.2 ^{A,B}	0.3 ± 0.0 ^{A}	0.6 ± 0.2 ^{B}	*
20:4n6	1.6 ± 0.4 ^{A}	2.0 ± 0.8 ^{A}	3.6 ± 0.9 ^{B}	**
20:3n3	0.2 ± 0.1	0.2 ± 0.0	0.2 ± 0.2	
20:5n3	3.9 ± 0.8 ^{A}	5.7 ± 0.8 ^{A,B}	8.6 ± 4.5 ^{B}	*
22:5n3	0.9 ± 0.6	1.4 ± 0.3	1.8 ± 0.7	
22:6n3	7.3 ± 1.5 ^{A}	9.7 ± 1.9 ^{A,B}	12.3 ± 3.2 ^{B}	*
ΣPUFA	35.3 ± 2.7 ^{A}	33.9 ± 2.1 ^{A}	44.2 ± 2.9 ^{B}	**
Σ n3	15.0 ± 2.2 ^{A}	18.5 ± 1.5 ^{A,B}	24.7 ± 7.4 ^{B}	*
Σ n6	20.4 ± 1.0	15.4 ± 1.2	19.5 ± 5.0	
n3/n6	0.7 ± 0.1	1.2 ± 0.1	1.4 ± 0.9	

^{A,B} = The values in the same row with a different letter are significantly different * = $p < 0.05$, ** = $p < 0.01$, ΣSFA, sum of essential fatty acids; ΣMUFA, sum of monounsaturated fatty acids; ΣPUFA, sum of polyunsaturated fatty acids; n3 and n6, are omega-3 and omega-6 polyunsaturated fatty acids respectively. Adapted from ref. [17].

In all the analyzed samples, the most representative fatty acid of monounsaturated fatty acid was oleic acid. It ranged from 25% to 37.5%, which agrees with previous results about fatty acids analyses in the meat from both *A. baerii* and *A. transmontanus* [74,75,77,78]. Higher monounsaturated fatty acids values were obtained in the meat of Siberian Sturgeons (45.5%) and female White Sturgeons (42.7%) than in that of male White Sturgeon (31.5%) [17].

The omega n3/omega n6 ratio range was 0.7–1.4 without any significant differences. These results are lower than the values (around 4) formerly published in the literature for *A. baerii* and *A. transmontanus* fillets [74,75,77]. It is worth mentioning that this difference is strongly impacted by linoleic acid content that, in this study, was 4-fold higher than that indicated by the aforementioned authors (11.9–16.1%). This difference can be easily explained by the modifications in aquafeed formulations that have taken place in recent years to maintain producer costs and to enhance aquaculture sustainability, e.g., replacing fish meal and oil with vegetable ones [44] enriched in linoleic acid. The highest decosahexaenoic acid (DHA) and eicosapentanoic acid (EPA) levels were found in the samples of male White Sturgeon meat (8.6% and 12.3%, respectively), followed by female White Sturgeon meat (5.7% and 9.7%) and female Siberian Sturgeon meat (3.9% and 7.3%). The high DHA and EPA levels in the analyzed samples should be taken into account because these fatty acids are strictly related to the product's nutritional quality, which is apparently characterized by low lipid content of high nutritional value.

The high proportion of essential n-3- fatty acids, e.g., DHA and EPA, is most important. The inherent DHA and EPA potentials for treating coronary heart disease, neurological and neurodegenerative disorders have been reported [79,80]. DHA and EPA are believed to have anti-inflammatory effects and play a role in oxidative stress [81]. They can improve cellular function through changes in gene expression [82]. In a study with human blood samples, DHA+EPA intake changed the expression of 1040 genes, which led to a drop in the expression of the genes involved in inflammatory- and atherogenesis-related pathways, such as hypoxia signaling, κB signaling, nuclear transcription factor eicosanoid synthesis, scavenger receptor activity and adipogenesis [82].

Apart from the above-discussed essential fatty acids, protein is another principal caviar and fish roe component. Generally, fish roe has, on average, 75% ovoglobulins, 13% collagen, and 11% albumin. Gong et al. [83] informed that the crude protein content of caviar samples fell within the 24.0–25.6% wet weight range. Glutamic acid (a mixture of glutamine and glutamic acid due to analytical matters) has been demonstrated as the most abundant amino acid (7.29–7.69%). Mol and Turan [84] identified aspartic acid (also aspartame and aspartic acid), glutamic acid, lysine and serine as major amino acids in Sevruga, Beluga and Osetra caviars. Omega-3 and omega-6 proportions in diet are determining factors for biochemical efficiency, which is vital in supplying optimal neurodevelopment conditions. Thus, approaching the ideal ratio of 2:1 or 1:1 can be relevant for neurodevelopment and prevent early neurodegeneration [85,86]. As the enzymes involved in the metabolism of alpha-linoleic acid (ALA) and linoleic acid (LA) are shared, competition exists between both, and omega-3 and omega-6 fatty acids regulate one another. Fish roe is known to also contain lysozyme, which is a substantial antibacterial agent [87].

The balance between ALA and LA and their polyunsaturated fatty acid metabolites in the diet is vital. In biological development, the human brain is the most outstanding organ. In the brain, the balance between omega-3 and omega-6 PUFA metabolites comes close to 1:1 [88]. Excessively large amounts of omega-6 PUFA and a very high omega-3 to omega-6 ratio frequently appear in western diets, and promote the pathogenesis of many diseases, including cancer, cardiovascular disease, inflammatory and autoimmune diseases, and also interfere with normal brain development [89,90].

One example of utilizing the nutritional benefits of sturgeon fillet powder to produce snack food has been investigated. A study fortified biscuits with more than 7% sturgeon fillet powder, which affected the rheological property of dough and the sensorial properties of biscuits [91]. Adding up to 7% sturgeon fillet powder can be employed to enrich the protein content of biscuits without affecting their individual sensory attributes and overall consumer acceptability. The results of this study envisage the possibility of gaining insights for further research works to provide important information about effective sturgeon usage to fight malnutrition problems [91].

6. Conclusions

Sturgeon offers excellent nutritional and health benefits that can help to improve food security, especially amongst communities of indigenous fishers. Further research on value addition is necessary to utilize the meat, caviar or eggs from the different species of this fish in new food products and cosmetics. The possibility of value addition to sturgeon fish will result in better purchasing power and resilience to food insecurity in these communities. Aquaculture will further help to improve the supply of this highly nutritious fish, reduce its cost and it can be included as a food ingredient in new food products developed by food business operators. It is highly recommended to investigate how thermal processing will affect flavor and other sensory attributes of sturgeon meat. Animal welfare to reduce pre-slaughter stress and better humane slaughter methods in sturgeon processing are also worth considering.

Aquaculture is useful in promoting the availability of sturgeon or its hybrids in many countries especially those with limited water resources, making it more available and affordable with low-cost breeding. Sturgeon supply (wild and domesticated) needs to remain sustainable in the long run, and efficient sturgeon breeding and harvesting management has to be carefully monitored. As highlighted in this study, the concern for fraudulent practices that imitate high-quality sturgeon products needs to be properly addressed. Digital tools during production, storage, distribution and consumption to ensure transparency and authenticity in the sturgeon value chain should be considered in the future.

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