

REVIEW

FROM LUXURY TO RESPONSIBLE CONSUMPTION: NUTRITIONAL AND ENVIRONMENTAL PERSPECTIVES ON THE PRODUCTION OF SIBERIAN STURGEON CAVIAR (*ACIPENSER BAERII*, BRANDT, 1869)

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Abstract: Caviar is a fish-based food product of high gastronomic and economic value, traditionally associated with luxury cuisine, but increasingly examined in the context of sustainability and responsible aquaculture. This review paper summarizes current information on the consumption of caviar derived from the Siberian sturgeon (*Acipenser baerii* Brandt, 1869), from nutritional, technological, and ecological perspectives. The chemical composition and biological value of caviar are analyzed, with an emphasis on proteins, Omega-3 polyunsaturated fatty acids (EPA and DHA), essential vitamins and minerals, as well as their effects on human health. The paper highlights the biological characteristics of sturgeons and their implications for sustainable caviar production. It also presents the main stages of the technological process for obtaining and processing caviar, as well as the influence of modern aquaculture systems on product quality and the conservation of natural resources. The review also addresses issues related to food safety, contaminants, traceability, and the environmental impact of intensive farming practices. Furthermore, it discusses the main challenges and prospects for the caviar industry, including the development of sustainable technologies and the reduction of pressure on wild sturgeon populations. The reviewed literature highlights that modern caviar production can integrate the product's nutritional and gastronomic value with the principles of sustainable development and the conservation of aquatic biodiversity.

Keywords: aquaculture, caviar, nutritional value, sustainability, wild

INTRODUCTION

Caviar, defined as the salted and matured roe obtained exclusively from fish of the sturgeon family (*Acipenseridae*), represents one of the most prized food products of aquatic origin, being associated with both gastronomic excellence and remarkable nutritional value [1]. Dubbed "black gold", caviar has been a symbol of refinement and social status since antiquity, retaining its exclusive character to this day, with prices varying according to species, origin, and quality, from a few hundred to several thousand euros per kilogram [2 – 4]. Beyond its prestige, caviar is recognized as a functional food [2] owing to its complex biochemical composition: high-quality proteins with a complete essential amino acid profile, polyunsaturated fatty acids (PUFA) particularly EPA and DHA, phospholipids, fat-soluble vitamins, and bioactive compounds with antioxidant and immunomodulatory properties [5 – 9]. These compounds are associated with beneficial effects on cardiovascular and neurological health, offering the organism protection against oxidative stress [9, 10]. Nevertheless, the high economic value and sustained global demand have generated significant pressures on sturgeon populations, which have experienced a dramatic decline since the second half of the twentieth century, driven by overexploitation, poaching, habitat fragmentation through dam construction, and aquatic environmental pollution [10, 11]. Consequently, sturgeons are currently considered the most critically endangered group of species on the planet, according to the IUCN (International Union for Conservation of Nature) Red List [9, 12]. Almost the entire commercial production of caviar today originates from aquaculture farms, which allow for the control of rearing conditions, the reduction of environmental impact, and the assurance of product traceability; however, they continue to raise challenges relating to sustainability and resource-use efficiency [3, 10]. In parallel, consumer behavior and market dynamics play an essential role in shaping the future of this industry. The expansion of the market towards the middle class and the emergence of alternative products (that is, caviar substitutes derived either from other fish species, or from cheaper sources, or even from plant-based materials that mimic the texture and appearance of caviar) have altered the perception of caviar, generated new opportunities but also risk, including a rise in fraud and illicit trade [3, 13, 14]. Within this complex context, the aim of the present article is to analyze caviar from the perspective of its nutritional value and health impact, in correlation with the challenges surrounding sustainable production and sturgeon conservation, highlighting the role of modern aquaculture and responsible consumption in securing the future of this resource.

MATERIALS AND METHODS

For the preparation of the present work, a systematic analysis of the scientific literature was carried out using the Google Scholar, ScienceDirect, Web of Science, Scopus, PubMed, and ResearchGate databases, as well as official FAO and IUCN reports. Relevant publications were identified on the basis of predefined keywords, selected according to year of publication, scientific relevance, and article type. On the Web of Science platform, works were searched using two series of keywords, namely: *sturgeon*, *caviar*, *aquaculture*, *nutrition*, *fatty acids*, *omega-3* and *sturgeon conservation*, *IUCN*, *endangered species*, *caviar production*, *food safety*, *bioactive compounds*. Excluded from

the analysis were studies published prior to 1980, articles written in languages other than English or Romanian, works without access to the full text, conference abstracts and editorials containing no original data, as well as studies with incomplete or insufficiently documented methodology. Duplicates identified across the consulted databases were likewise removed. By combining the two series and applying the inclusion and exclusion criteria, a total of 100 studies were selected and included in the final analysis.

RESULTS AND DISCUSSION

Sturgeon biology and its implications for sustainable caviar production

Sturgeons (*Acipenseridae*) are distinguished by a set of unique biological characteristics that confer upon them a high economic value whilst simultaneously rendering them extremely vulnerable to anthropogenic pressures [15, 16]. Understanding these particularities is essential for explaining the decline of wild populations and for underpinning the transition towards modern sustainable production systems [9, 10, 11]. The Siberian sturgeon (*Acipenser baerii*) displays a complex reproductive cycle, characterized by the asynchronous development of the gonads and irregular spawning intervals (Figure 1).

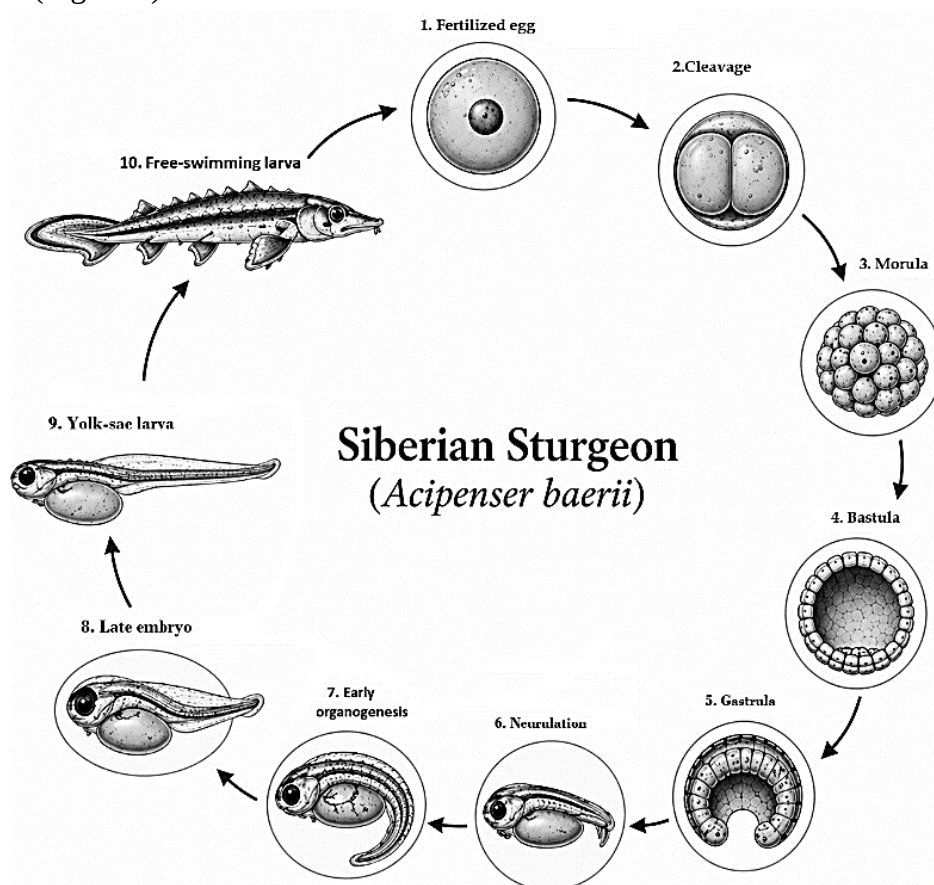


Figure 1. Stages of embryonic development in the Siberian sturgeon (*A. baerii*), adapted from Fopp-Bayat et al., (2022) [21] and Park et al. (2022) [22]

Unlike the majority of fish, females do not ovulate annually, with reproduction occurring at intervals of two to three years or even longer in the case of mature specimens [17, 18]. Sexual maturity is reached late and varies according to environmental conditions. In some populations, for instance, males attain maturity at nine to eleven years of age, whilst females do so between ten and seventeen years [19, 20]. This slow development significantly reduces the capacity of populations to recover. The natural spawning environment directly influences both the embryo survival rate and the adaptations of the roe to disruptive factors. In the wild, sturgeons deposit their eggs on gravel or rock substrates in rivers with considerable depths and moderate to rapid currents. These conditions ensure optimal oxygenation, whilst the envelope of the fertilized eggs becomes adhesive, allowing them to attach to stones and preventing their dispersal by currents [23]. Adaptation to such habitats has favored the evolution of high mechanical resistance in the eggs, particularly in long-distance migratory species. In this regard, *Huso huso* and *A. baerii* produce more resilient eggs compared to *Acipenser stellatus*, which spawns in areas situated further downstream [24]. From an ecological standpoint, the majority of sturgeons are migratory species, and their reproductive success is closely dependent on the integrity of natural habitats. The Siberian sturgeon, for instance, is an anadromous species that travels from marine environments to freshwater for reproduction [20]. Spawning takes place under strictly determined conditions of temperature and water current dynamics, which renders these species extremely vulnerable to anthropogenic modifications of their habitat [19].

Concurrently, dam construction has fragmented riverine ecosystems, blocking migration routes to natural spawning grounds and disrupting the aquatic habitats of sturgeons [23, 25]. As a consequence, sturgeons are compelled to spawn in restricted areas, resulting in excessive egg densities, increased mortality during incubation, and impaired oogenesis viability [24]. These characteristics late maturity, intermittent reproduction, and dependence on specific habitats define a vulnerable life strategy that limits the capacity to adapt to rapid environmental disturbances [15, 16]. The biological characteristics of sturgeons account for their extreme vulnerability to anthropogenic pressures. In the second half of the twentieth century, natural populations experienced a significant decline driven by a combination of factors [9 – 11]. Among these, overexploitation and poaching played a major role, fueled by the high demand for caviar, a luxury product of considerable economic value [9, 10]. Concurrently, industrial and agricultural pollution degraded water quality, reducing the survival rate of juveniles and promoting the accumulation of contaminants in adult organisms [26]. Furthermore, the high longevity of sturgeons contributes to the bioaccumulation of toxic substances, including heavy metals and persistent organic compounds [3].

Modern aquaculture systems allow for the strict control of environmental conditions, reducing pressure on natural ecosystems and ensuring product traceability. A pertinent example is provided by recirculating aquaculture systems (RAS), which optimize water use and limit environmental impact [27].

Aquaculture also contributes to the reduction of contaminants in the final product through the use of water recirculation systems, which allow precise control of water quality parameters such as temperature, dissolved oxygen levels, ammonia, nitrate and nitrite concentrations, as well as disinfection via UV irradiation or ozonation [28, 29]. These closed-circuit systems filter and recirculate water, eliminating dependence on potentially contaminated external sources and thereby reducing sturgeon exposure to environmental

pollutants. Consequently, caviar derived from aquaculture generally presents lower contaminant levels compared to that from wild sources [30].

The influence of sturgeon diet on caviar quality

The feed of sturgeons profoundly influences the quality, biochemical composition, sensory properties, and commercial value of caviar, with the most significant effects being determined by the lipid composition of the diet [31]. Whilst dietary proteins play a relatively minor role in the final characteristics of the roe, lipids and the fatty acid profile of feed directly shape the flavor, nutritional value, and caviar yield [9, 31].

The fatty acid composition of the roe, particularly the triacylglycerol fraction, directly reflects the lipid profile of the feed administered to sturgeons [9, 32]. Accordingly, one of the principal differences between farmed and wild caviar is the higher linoleic acid (Omega-6) content and the reduced level of arachidonic acid (ARA) in cultured sturgeons [7, 32]. This difference is attributable to the frequent use of vegetable oils such as soybean, sunflower, maize, or rapeseed oil in commercial feed formulations, as a cost-effective alternative to fish oil [7, 9]. The reduced level of ARA in farmed caviar is further explained by the limited capacity of sturgeons to convert linoleic acid into arachidonic acid [32]. In the natural environment, ARA is available in greater quantities through the aquatic food chain, particularly via the consumption of algae and crustaceans, which accounts for the higher values found in wild caviar [9]. By contrast, the deposition of essential Omega-3 fatty acids, such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), occurs selectively in the roe and is less influenced by diet, with both caviar types frequently presenting similar concentrations of these compounds, which are important for embryonic development and nutritional value [7, 9]. Dietary fats visibly influence the flavor of caviar, as off-flavors and unpleasant tastes are often caused by lipophilic compounds stored in the eggs during the vitellogenesis process [31]. The principal sources of these compounds, deriving both from artificial feeds used in aquaculture and from the natural aquatic environment, include the following:

Phytoplankton, cyanobacteria, and actinomycetes (particularly *Streptomyces* spp.), together with myxobacteria, significantly influence the sensory profile of caviar, especially in aquaculture systems [33 – 35]. Although they do not constitute intentionally administered feed, these microorganisms are ingested by fish and represent the principal source of compounds responsible for the occurrence of undesirable off-flavors. These compounds include geosmin and 2-methylisoborneol (MIB), lipophilic substances that accumulate in adipose tissue and oocytes during vitellogenesis [3]. They impart characteristic odors of “earth”, “mud”, or “mold”, which adversely affect the sensory quality of the final product. Furthermore, certain eukaryotic algae may contribute through the production of beta-cyclocitral, associated with “woody” or “tobacco” olfactory notes [10]. Consequently, the sensory profile of caviar is strongly dependent on the microbiological composition of the aquatic environment, which necessitates strict control of aquaculture conditions in order to maintain product quality [34 – 36].

Commercial feeds and vegetable oils: A major source of unpleasant flavors is the degradation of lipids assimilated from feed. Feeds contain high quantities of polyunsaturated fatty acids (PUFA), such as linoleic and linolenic acids, which frequently derive from vegetable oils used in aquaculture. These lipids are unstable and prone to oxidation reactions or enzymatic catabolism. Their breakdown leads to the formation of

aldehydes (e.g. hexanal, heptanal, nonanal), alcohols (e.g. 1-octen-3-ol), and ketones, which impart to caviar a rancid or waxy odor, notes of "spoiled fish", or undesirable "green" notes [7, 10, 34].

Lactones and terpenes from feed ingredients: These classes of aromatic compounds, identified in sturgeon fillets and caviar, are of external origin. They derive either from the oxidation of fatty acids or may be absorbed directly by the fish from commercial feed ingredients and ingested phytoplankton. These compounds add notes that may alter the aromatic profile of caviar [34].

Aversive compounds from natural food sources: Certain invertebrate and vertebrate organisms consumed by sturgeons under natural feeding conditions contain toxic compounds or substances with unpleasant taste and odor, which exert a strong feeding deterrent effect and possess very low palatability, potentially transferring undesirable flavors to the flesh of the fish [37].

Feeds are carefully formulated with regard to the fat-to-energy ratio, as an appropriate level is essential for obtaining a superior quality product [31]. Inadequate nutrition or an incorrect feeding ration may limit fish growth and adversely affect the development of the reproductive system, to the extent of inhibiting normal gonadal development [31]. During vitellogenesis (the process of yolk formation), fatty acids are mobilized directly from the adipose reserves of the sturgeon and incorporated into oocytes; consequently, the quality and baseline lipid composition of caviar are intrinsically dependent upon what the fish has consumed [9, 31].

The sensory profile of caviar varies significantly depending on whether the fish has been reared in freshwater or brackish water. The presence of undesirable off-flavors such as isoborneol or geosmin is determined by volatile compounds produced by filamentous bacteria of the actinomycete type (particularly *Streptomyces spp.*), cyanobacteria (*Anabaena*, *Oscillatoria*, *Pseudanabaena*), and myxobacteria, which develop frequently in aquaculture systems, making rigorous environmental control obligatory [34, 35].

In order to optimize aquaculture production and to obtain a caviar that emulates the superior qualities of its wild counterpart, specialists recommend the development and use of improved feeds in which the level of linoleic acid is reduced and that of arachidonic acid is increased [7, 32]. Based on research in the field, the principal recommendations concern the following aspects:

a. Low-fat, high-protein diets

Studies have shown that feeding a low-fat diet, consisting of approximately 47 % protein and 8-9 % fat, is a crucial factor in achieving excellence in caviar production and optimizing yield [38]. Another experiment, conducted on the (*Acipenser ruthenus*), also yielded significant results for caviar yield using commercial feed with a slightly higher protein content of 53 % and 13 % fat, administered at a moderate rate of 0.75 % of body weight [39].

b. Strict monitoring of periovarian fat accumulation

Nutrition and feed ration levels are critical parameters because an unbalanced diet promotes the accumulation of periovarian fat at the expense of gonadal development [3]. Excessive periovarian fat directly affects farm efficiency and economic profits, as it reduces the quantity (yield) of harvested caviar and requires additional labor for the separation, cleaning, and processing of the eggs [38, 40]. For this reason, feeding strategies that limit fat accumulation in young sturgeon are recommended [38].

c. Optimization of lipid sources

The type of oils used in feed directly influences productivity. It has been observed, for example, that adding squid oil to the diet of sturgeon resulted in an increase in egg yield compared to diets that used soybean oil as the main source of lipids [6].

d. Adjustment of the fatty acid profile

To support optimal reproductive development and good performance, it is recommended that feed formulations mimic the nutritional composition of the diet of wild sturgeon. Thus, the linoleic acid content (found abundantly in vegetable oils commonly used in commercial feeds) should be reduced, and the arachidonic acid content increased [32]. Furthermore, ensuring an optimal level of long-chain polyunsaturated fatty acids (PUFA), particularly those of the n-3 series (such as EPA and DHA) is vital, a deficiency in these affects fish health, reduces feed conversion efficiency, and impacts the quality and yield of egg production [41, 42].

The caviar production process

The technological process for producing caviar is a complex procedure comprising several essential stages that require strict hygiene controls and low temperatures [43]. The main stages, from fish selection to the finished product, are illustrated in the following diagram (Figure 2):

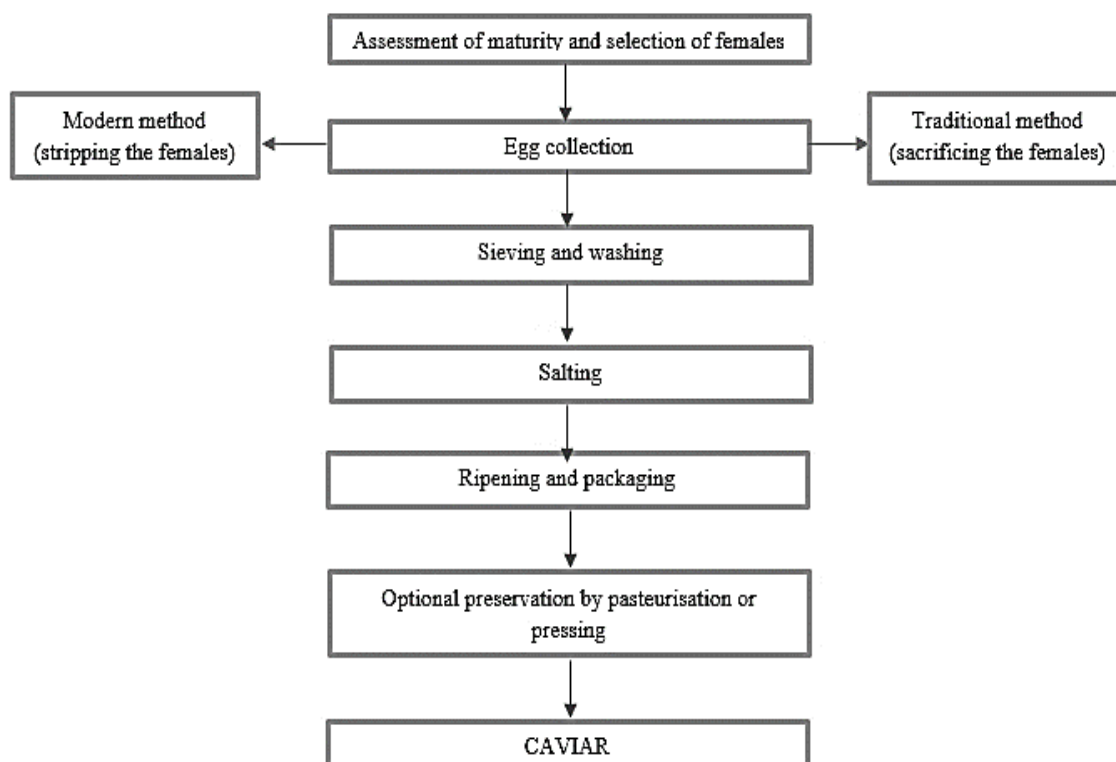


Figure 2. The caviar production process

The first stage, considered the most important in the process, consists of selecting females that have reached the optimal level of maturity [43]. Farmers assess the stage of the eggs

(size, color, firmness) using ultrasound or biopsy in order to determine the precise moment of harvesting, before natural spawning occurs [10, 44, 45]. Once selected, egg extraction may be carried out by two principal methods:

- The traditional method (with slaughter): The fish is washed to remove mucus and contaminants, after which it is stunned by percussive stunning (a blow applied to the posterior brain, along the median line, between the two spiracles) or by electronarcosis (electrical stunning in a water bath), methods recommended by both the World Organization for Animal Health (WOAH) and the European Food Safety Authority (EFSA) as humane procedures for sturgeons [28, 46]. The gills are subsequently cut for bleeding, a procedure lasting two to three minutes [10]. An abdominal incision is then made and the ovaries (ovarian sacs) are extracted very rapidly [10]. This prevents the post-mortem release of enzymes that would compromise product quality or could even cause illness [43].
- The “no-kill” method (ethical caviar) represents an innovation in aquaculture that permits the harvesting of eggs without slaughtering the females, offering the possibility of repeated use of the same specimen and thereby reducing pressure on biological resources, even though slight modifications to the texture of the final product may occur [3, 45, 47 – 49]. The process involves the induction of ovulation through hormonal treatments, using either carp pituitary extract (CPE) or synthetic analogues of gonadotropin-releasing hormone (GnRH/LHRH-a), administered intramuscularly or via slow-release implants, which causes the eggs to be released into the abdominal cavity [10, 45, 50]. The eggs are subsequently extracted by gentle abdominal massage, without lethal intervention on the fish. Following harvesting, the product requires a stabilization process to prevent membrane alterations, either through mild heat treatment (immersion in water at approximately 60 °C) or through immersion in cold water with pH adjusted between 6.8 and 8.0, so that the structure and consistency of the eggs are adequately maintained [10, 44]. Additionally, the use of ultrasound contributes to sex determination and gonadal maturity assessment in a non-invasive manner, with a reduced level of stress for the fish [51].

In traditional processing, the ovarian sacs are gently rubbed by hand through special sieves to separate the eggs from the membrane and connective tissue that holds them in place [43, 52]. Once separated, the eggs are repeatedly washed with cold water to remove impurities, blood, membrane remnants, and broken eggs, after which they are drained [10, 43]. Following cleaning, the eggs are weighed and salted by hand [10]. The highest quality is achieved through the "Malossol" technique (lightly salted), which involves adding a very small quantity of salt (between 2 % and 5 %), its role being both to preserve the product and to enhance its delicate flavor [10, 52]. Traditionally, in addition to salt, a small quantity of sodium tetraborate (borax) may also be used, a preservative that imparts a slightly sweet taste to the product [43]. The use of borax has, however, been prohibited in certain countries (such as the United States) owing to its degree of toxicity, being permitted only within strict limits in the EU [53].

The salted eggs are firmly packed into large tins (typically of 1.8 k) or polypropylene containers that allow for the elimination of air and excess liquid produced by the action of the salt [43, 54]. After sealing in an oxygen-free environment, the caviar is left to mature in a refrigerated chamber at a temperature between -2°C and +4°C, for a period

ranging from a few weeks to one year [43, 54]. The maturation process is essential for the development of the specific aromatic profiles sought by consumers [54].

To extend shelf life, caviar may be pasteurized [43]. The treatment must be carried out at mild temperatures (50-70 °C) to avoid protein coagulation, which would transform the eggs into a cooked mass with a rubbery texture [1]. A further secondary option is pressed caviar (*pressed caviar / payusnaya*), processed from defective ovaries or lower-quality eggs, which are submerged in saturated brine at temperatures between 38 °C and 45°C and pressed until they reach a marmalade-like consistency [10, 43].

Caviar production and sustainability

Historically, sturgeons were extraordinarily abundant fish, with global catches reaching a peak of approximately 32,000 tons in 1977, particularly in the Caspian Sea and Black Sea regions [55]. During the peak period of wild sturgeon fishing (1979-1989), global caviar production regularly exceeded 3,000 tons annually [11]. With the dramatic decline of natural populations and the imposition of fishing restrictions, production has been redirected almost entirely towards aquaculture farms, which today represent the principal source of legal caviar on the market [3, 56]. At the beginning of the expansion of sturgeon farms, in 2008, global farmed caviar production stood at approximately 110-120 tons [55]. This quantity increased rapidly as the fish reached maturity, surpassing 260 tons in 2012 [56]. Subsequent data indicate continued growth, with global production estimated at approximately 340 tons in 2016 and 364 tons in 2017 [11]. The most recent analyses report a global production that has risen steadily, reaching a peak of 592.74 tons in 2019, followed by a slight adjustment to 571.9 tons in 2020 [57]. Other updated estimates place the current level of production at approximately 700 tons per year [58]. China dominates the market decisively, accounting for between one third and over 80 % of global production and exports, followed by major producers such as Denmark, Russia, Italy, France, and the United States [57]. Looking ahead, projections indicate that production will continue to grow, as many farmed sturgeons have not yet reached the optimal age for harvesting, and global volumes could reach as much as 2,000 tons annually [3, 56]. This growth outlook raises concerns regarding potential overcapacity, with experts warning that supply could outpace demand, which may lead to a decline in prices and profitability for farms [11].

Despite the marked decline of wild populations, global demand for caviar and sturgeon meat has remained high owing to the product's luxury status, nutritional value, and the expansion of international markets [3, 10], highlighting a major paradox: rising global demand in conditions of severe limitation of natural resources. The interdependence between the biology of sturgeons, production methods, and consumer behavior is essential for the sustainability of the sector. Although aquaculture reduces pressure on wild populations, sturgeon farming involves significant consumption of water, feed, and energy, making it necessary to optimize production systems through the use of renewable energy sources and improvements in feed conversion, in order to reduce the carbon footprint [63]. The differences between farmed and wild caviar are summarized in Table 1.

Table 1. Differences between farmed and wild caviar

Characteristic	Farmed caviar	Wild caviar	References
Origin	Controlled farms (RAS or open systems)	Natural ecosystems (rivers, seas)	[3]
Availability	stable, predictable	Very limited, restricted	[10]
Environmental impact	Low (if sustainably managed)	High (overexploitation, poaching)	[11]
Contaminant content	Low (control of water and feed)	Higher (bioaccumulation)	[26,30]
Fatty acid profile	Influenced by diet (higher linoleic acid content)	Natural (higher arachidonic acid content)	[32,64]
Traceability	High (complete production control)	Limited / uncertain	[65]
Legality	Legal, regulated	Often restricted or illegal	[66]
Quality and uniformity	Consistent	Variable	[3]
Production cost	High (resources, long rearing period)	Variable (but very high ecological cost)	[63]
Sustainability	High (if standards are met)	Very low	[9]
Role in conservation	Protects wild populations	Contributes to their decline	[67]

A comparison of the two sources of caviar highlights the major advantages of aquaculture in terms of sustainability, food safety, and traceability. While wild caviar has a natural profile, it is associated with significant ecological risks, which is why aquaculture currently represents the viable alternative for the conservation of sturgeon species [3, 10, 11].

The ecological environment plays a crucial role in determining the quality of the eggs, directly influencing their sensory and biochemical profile as well as their yield. The thermal regime directly affects fatty acid metabolism and gonadal development in sturgeons [59]. A period of maintaining fish at lower water temperatures during winter (approximately 10-13 °C) is often employed by farmers to reduce follicular atresia. By contrast, chronic thermal stress and poor water quality can directly inhibit ovarian development and reproductive success [23]. Ideal conditions presuppose good oxygenation; in aquaculture systems, it is recommended that dissolved oxygen levels be maintained consistently above the threshold of 5 ppm [60]. Toxic substances, such as nitrates that may accumulate in recirculating systems, act as endocrine disruptors, impairing reproductive function [61]. Nutrition is a fundamental factor that distinguishes farmed from wild caviar, as the controlled diet shapes both the quality and the biochemical composition of the eggs [32, 62].

Figure 3 synthesizes the relationship between the biological vulnerability of sturgeons, anthropogenic pressures, and modern sustainability solutions within the caviar industry. The biological characteristics of the species, combined with overexploitation and habitat degradation, have driven the decline of wild populations and the necessity of shifting towards sustainable aquaculture [11, 25, 68]. In this context, modern production systems, circular economy practices, traceability, and international regulations contribute to reducing the impact on natural resources and to supporting legal production [9, 27, 65].

The diagram also highlights the role of responsible consumption in species conservation and in supporting the sustainable development of the sector [13].

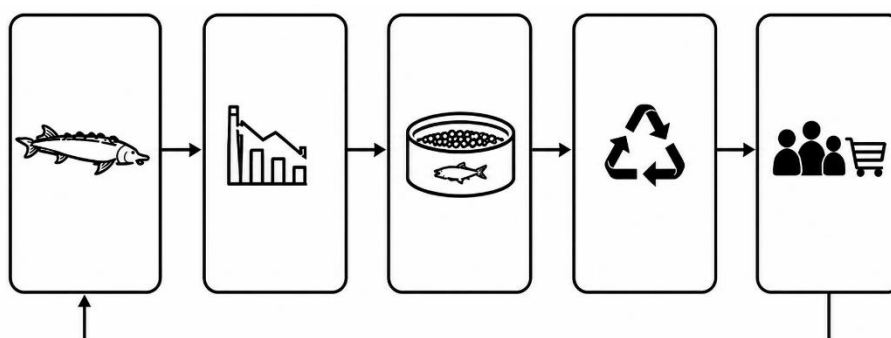


Figure 3. Sustainability plan for caviar

The development of modern production systems, particularly RAS, allows for water reuse and the control of environmental parameters, reducing dependence on natural resources, although these technologies require careful management of energy consumption and nitrate accumulation [27, 69, 70]. Concurrently, the use of alternative protein sources, such as *Hermetia illucens* larva meal, contributes to increasing the sustainability of aquaculture and to reducing dependence on finite marine resources [71].

The sustainability of the industry is further supported by strict regulations governing international trade. All sturgeon species were included in the CITES appendices (the Convention on International Trade in Endangered Species of Wild Fauna and Flora) between 1997 and 1998, and the commercialization of caviar is subject to mandatory labelling and traceability systems that include information regarding the species, product origin, country of provenance, and year of production [65, 66, 72]. Furthermore, modern molecular techniques such as DNA barcoding (species identification based on the sequencing of standardized mitochondrial DNA regions), microsatellite analysis (repetitive genetic markers used for individual genetic fingerprinting and determination of geographical origin), and the COI-Bar-RFLP method (a combined technique based on the amplification of the COI gene Cytochrome c Oxidase subunit I, followed by restriction enzyme digestion for the rapid discrimination between species) allow for the precise identification of species and the detection of commercial fraud [13, 73, 74]. Sustainability certifications such as MSC (Marine Stewardship Council an international certification body for responsible fishing) and other schemes dedicated to aquaculture further contribute to guaranteeing the responsible provenance of products [52]. Another central element of sustainability is the transition towards circular economy models. The modern industry makes full use of the sturgeon, utilizing not only the eggs but also the meat and by-products (skin, cartilage, and organs) in the food, cosmetic, pharmaceutical, and nutraceutical industries, thereby reducing waste and increasing resource-use efficiency [9, 63, 75].

Market transformations, in turn, influence the direction of development of the industry. The principal consumer markets are the European Union, the United States, Japan, Russia, Switzerland, and China, whilst sturgeon meat consumption presents significant regional differences, being more prevalent in Asia and Eastern Europe [56, 76]. In this context, the consumer plays an essential role in species conservation and in supporting sustainable production. Choosing certified and traceable products, accepting alternatives

derived from non-endangered species or plant-based substitutes, and avoiding illegal trade, sometimes associated with organized crime networks all reduce pressure on wild populations [43, 77 – 79]. In the long term, the future of the industry depends on the balance between global demand, species protection, and the capacity of aquaculture to produce responsibly, through the strict application of regulations, the development of sustainable technologies, and the accurate informing of consumers.

Chemical composition and health effects

Caviar (salted, unfertilized sturgeon roe) contains approximately 47.7-59.5 % water, 21.5-29.3 % protein, 13.2-16.2 % lipids, and 3.2-3.8 % mineral salts, with values being influenced by species, provenance (wild or farmed), processing methods, and degree of salting [2, 7, 9, 30, 80, 81]. Owing to the elevated proportion of proteins and lipids, the energy value ranges between approximately 210.94 and 271.45 kcal/100 g, depending on species [81].

Proteins

Caviar presents a complete essential amino acid profile, superior to FAO/WHO standards, with glutamic acid being the predominant amino acid responsible for both the nutritional value and the characteristic “umami” flavor of the product [52, 80 – 84]. An essential role in determining the protein composition is played by vitellogenins (VTG), lipo-glycophosphorylated proteins synthesized in the liver under the influence of estrogens and subsequently transported to the ovaries [28, 85, 86]. These are the precursors of vitellin and phosvitin major components of the protein fraction in the eggs and confer upon caviar high digestibility, superior biological value, as well as antioxidant and antimicrobial properties relevant to the protection of oocytes and product stability [86 – 89]. Certain sturgeon-derived peptides also exhibit significant antioxidant activity, contributing to the neutralization of reactive oxygen species and to cellular protection [86, 90].

Lipids

The lipid fraction is dominated by polyunsaturated fatty acids (PUFA), particularly EPA and DHA (Omega-3), but also includes monounsaturated fatty acids (predominantly oleic acid), Omega-6 fatty acids (linoleic and arachidonic acid), and saturated fatty acids (principally palmitic acid) [2, 9, 80]. The lipid profile differs between wild and farmed caviar, with variations being largely influenced by the diet and rearing conditions of the sturgeons [9].

Micronutrients

Caviar represents an important source of both fat-soluble and water-soluble vitamins particularly vitamins A, D, E, B12, and C as well as essential minerals, including iron, calcium, magnesium, copper, and selenium [2, 9, 80]. The high sodium content is associated with the salting preservation process.

Compared to other types of roe, caviar presents a balanced nutritional profile and a high density of essential nutrients. Salmon roe generally contains higher concentrations of Omega-3 fatty acids and a superior Omega-3/Omega-6 ratio; however, both products constitute valuable sources of proteins, bioactive lipids, vitamins, and minerals [91, 92]. The principal differences between the two product types are presented in Table 2.

Table 2. Differences between sturgeon caviar and salmon roe

Characteristic	Caviar	Salmon Roe	References
Protein content (%)	21–29%	20–30%	[80, 81]
Lipid content (%)	14–15%	>14–15%	[10]
Total Omega-3 (%)	moderate	high (>32%)	[91]
EPA (%)	2.8–5.3%	~17.8%	[91]
DHA (%)	high	high	[91, 92]
Omega-3 / Omega-6 ratio	2.56–3.59	~8.06	[91]
Vitamin B12	very high	high	[9]
Vitamins A, D, E	present in significant quantities	present	[9]
Minerals (Fe, Zn, Se, Ca)	rich	rich	[61]
Nutritional density	very high	very high	[92]
Lipid profile	balanced	richer in Omega-3	[91]
Contaminant risk	variable (higher in wild)	moderate	[26, 30]

Furthermore, farmed caviar tends to present a more controlled composition and lower contaminant levels compared to that derived from wild sources [3, 30].

Health benefits

Moderate consumption of caviar is associated with beneficial cardiovascular effects reduction of triglycerides, diminishment of systemic inflammation, and inhibition of platelet aggregation contributing to a reduced risk of coronary heart disease and stroke [9, 77, 94]. EPA and DHA also play an important role in the development and maintenance of cognitive functions and in the prevention of neurodegenerative decline [2, 10]. Oleic acid contributes to the reduction of oxidative stress and LDL cholesterol [2], whilst proteins, bioactive peptides, vitamins, and minerals support immune system functioning and essential metabolic processes [2, 10].

Risks and limitations of consumption

The salting preservation process results in a high sodium content (2–6 %, sometimes exceeding 8 %), associated with an increased risk of arterial hypertension and renal disorders [1, 9, 10]. The product also contains cholesterol (0.1–0.3 %), a consideration relevant to restrictive diets [92, 95]. Being a raw or minimally processed product, caviar may present microbiological risks under improper storage conditions, including contamination with *Clostridium botulinum* [1, 3]. As long-lived species at the top of the food chain, sturgeons may bioaccumulate pollutants such as mercury, DDT (dichlorodiphenyltrichloroethane), and PCBs (polychlorinated biphenyls), whilst the contamination of aquatic environments with microplastics represents an emerging issue with potential implications for food safety [26, 31, 97, 98]. Risk assessment methodologies based on exposure and toxicity indices, applied to other animal-derived food products contaminated with heavy metals, indicate that consumer risk varies significantly by age group, with adults typically showing higher exposure levels than children [99]. In Romanian freshwater ecosystems, microplastic ingestion has already been documented in native cyprinid species such as *Squalius cephalus*, confirming that this contamination pathway is already present in riverine habitats relevant to sturgeon aquaculture [100]. Nevertheless, given the relatively low consumption of caviar, the overall risk to human health remains limited [97].

Authentication and differentiation of caviar origin

The differentiation of caviar origin is based on several biochemical and analytical criteria. The fatty acid profile represents an important indicator, reflecting the diet of the sturgeons and their rearing conditions [30, 32]. Linoleic acid is present in higher concentrations in farmed caviar, owing to the use of plant-based feeds, whilst arachidonic acid is more abundant in wild caviar, reflecting the natural diet of the fish [32]. Furthermore, the use of specific fatty acids as artificial markers allows for the monitoring of product traceability and the identification of its origin [48, 93, 94]. Contaminant analysis also constitutes a relevant criterion, with wild caviar frequently presenting higher levels of toxic substances [26, 30]

Challenges and future perspectives in the caviar industry

The global caviar industry has undergone a historical transition from the exploitation of wild resources to an almost total dependence on aquaculture, a process accelerated by the dramatic decline of natural sturgeon populations and the international fishing and trade bans imposed at the end of the twentieth century [3, 56]. Nevertheless, the rapid development of the aquaculture sector faces major obstacles whilst simultaneously opening new horizons of opportunity.

Major challenges in the caviar industry***Long production cycles and high operational costs***

Sturgeon farming is a labor-intensive process, as sturgeon grow slowly and reach sexual maturity late, which can range from 3 to 18 years depending on the species [63]. This ties up farmers' capital for long periods before any profit is realized and involves labor-intensive work, costly water filtration systems, and high feed expenses [101].

Illegal trade, fraud, and pressure from substitutes

Even with strict regulations (CITES), poaching and the black market for caviar from wild stocks remain active, fueled by attractive prices [77]. At the same time, the legal industry faces the phenomenon of “commercial mimicry”: the massive proliferation of caviar substitutes (made from lumpfish, salmon, or other species roe, or from plant/animal sources that mimic caviar), which are sold at rock-bottom prices and create confusion among consumers, eroding the market share of genuine caviar [10, 55].

Animal welfare

Producing traditional caviar requires the slaughter of females. In an effort to address sustainability concerns, farmers have introduced multiple harvesting methods (“no-kill caviar”/extraction via massage or cesarean section). However, recent studies show that these practices raise ethical concerns and cause fish suffering, involving invasive surgical procedures, anesthesia, and extreme stress, which calls into question the “ethical caviar” label [47].

Future prospects and innovations

Biotechnological innovations

One of the most promising technological solutions is Early Sex Determination (ESD) in sturgeons. The use of genetic methods allows the separation of females from males as early as the first three to six months of life. This leads to a major reduction in the costs associated with feeding and rearing males, increasing the economic profitability of farms by 9–34% and significantly reducing environmental impact [55, 63].

Functional applications and non-food use

In addition to its culinary use, caviar and sturgeon by-products have important applications across various industries, and their full valorization aligns with the principles of the circular economy and the "zero-waste" model [9, 76, 101]. In cosmetics, caviar extracts rich in bioactive peptides, amino acids, and Omega-3 fatty acids are used in anti-ageing and cellular regeneration products, contributing to the stimulation of collagen synthesis and the improvement of skin appearance [8, 9, 76]. In the nutraceutical and medical fields, by-products such as sturgeon cartilage, bone, and skin represent important sources of collagen, gelatine, and chondroitin, with applications in joint health and tissue engineering [9, 76]. Similar extraction protocols, based on collagen hydrolysis from meat-processing by-products, have demonstrated that extraction duration directly influences hydroxyproline yield and collagen structure, supporting the feasibility of applying comparable methods to sturgeon-derived by-products [102]. The leather industry makes use of sturgeon skin for luxury products, whilst the swim bladder is used to obtain isinglass, employed as a fining agent in the beverages industry [9, 76]. Since a farm focused exclusively on caviar is economically vulnerable, experts suggest diversifying revenue streams through the valorization of sturgeon meat via modern preservation and marketing methods (vacuum packed or smoked fillets), the use of by products for the extraction of bioactive substances destined for the cosmetic and pharmaceutical industries, and the transformation of processing waste into fishmeal, organic fertilizers, or animal feed [9, 76, 103].

The “Masstige” market strategy

In order to manage the substantial production volumes, experts recommend transforming social perception through the application of the “Masstige” (mass-prestige) strategy. This concept involves extending luxury products to the middle class by creating more accessible product lines whilst maintaining the illusion of scarcity and high-quality standards. The acquisition of new consumer categories must, however, be accompanied by clear labelling, transparency regarding production methods, and assurance of product authenticity [11, 63].

CONCLUSIONS

The analysis of the specialist literature highlights the fact that caviar produced from the Siberian sturgeon (*A. baerii*) represents a food product of exceptional gastronomic and nutritional value, characterized by a complex biochemical composition and a high density of essential nutrients. The significant content of high biological value proteins, Omega-3

polyunsaturated fatty acids (EPA and DHA), vitamins, and minerals confers upon this product important functional properties, associated with beneficial effects on cardiovascular health, cognitive function, antioxidant status, and immune response. Furthermore, the lipid profile and sensory characteristics of caviar are directly influenced by environmental factors, the diet of the sturgeons, and the rearing and processing technologies employed in aquaculture.

Concurrently, the analyzed literature underscores the high ecological vulnerability of sturgeons, determined by their slow biological cycle, late sexual maturity, and dependence on specific spawning habitats. Commercial overexploitation, poaching, dam construction, degradation of riverine habitats, and pollution have contributed to the severe decline of wild populations worldwide, transforming numerous sturgeon species into some of the most threatened groups of fish on the planet.

In this context, the development of aquaculture systems for *A. baerii* has consolidated itself as a strategic alternative for ensuring the availability of caviar and reducing the pressure exerted on natural resources. The analyzed data indicate that controlled production in aquaculture allows for the obtainment of caviar with a stable nutritional profile, enhanced traceability, and a reduced contamination risk compared to products derived from wild sources. At the same time, the optimization of feed formulation, reproductive management, and the control of rearing conditions directly influence the final product quality, reproductive yield, and the economic sustainability of fish farms. Thus, the integration of circular economy principles, the full valorization of biomass, and the reduction of impact on aquatic ecosystems become essential components of the sustainable development of the sector. Likewise, the maintenance of traceability and compliance with international regulations governing trade in sturgeon-derived products, including certification under the CITES Convention, represent fundamental instruments for limiting illegal trade and conserving aquatic biodiversity.

In conclusion, the transition "from luxury to responsible consumption" reflects the transformation of caviar from an exclusive product into a functional food obtained through sustainability-oriented practices. The current evolution of the sector demonstrates that the gastronomic and nutritional value of caviar can be compatible with the principles of natural resource conservation, responsible production, and the sustainable development of modern aquaculture.

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