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Review Article

Sturgeon Aquaculture Potentiality in Egypt in View of the Global Development of Aquaculture and Fisheries Conservation Techniques: An Overview and Outlook

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ABSTRACT

Sturgeon conservation is a global issue, with wild sturgeon amounts dropping rapidly and continuously. This article explores the essential role that aquaculture plays in the conservation of these critically endangered fish, the replenishing of the natural population, fulfilling the expanding demand and possibilities for caviar markets, and reducing pressure on fisheries' catch. It also reviews the history of controlled breeding programs designed to supplement wild Caspian Sea populations, the possibilities for sturgeon aquaculture production, and the worldwide caviar trade industry in the coming years. Globally, the successful and profitable expansion of captive sturgeon farming over the last three decades has fulfilled the consumer market's demand for caviar and meat, resulting in a considerable decline in the global caviar price. Given the presence of successful sturgeon farming in the Arabian Gulf region (Saudi Arabia and the United Arab Emirates), the prospect of introducing the sturgeon farming industry in Egypt is underlined. In comparison to other nations in the region, Egypt has excellent prospects for establishing such an aquaculture business, as Egypt's aquaculture sector is by far the largest in Africa and the sixth largest internationally. Furthermore, the availability of qualified workers, the diversity of water sources, and Egypt's moderate climate and environment increase the likelihood of successful sturgeon farming.

Keywords: Sturgeon, aquaculture techniques, fishery conservation, replenishment, caviar, Egypt

INTRODUCTION

The aquaculture industry plays a crucial role by providing nearly half of the animal protein required globally (Abdel-Rahim et al., 2023; Shahin et al., 2023), and doubling per capita human consumption from 9.9 kg in the 1960s to more than 20.2 kg in 2020 (FAO, 2022). In 2020, global fisheries and aquaculture yielded 214 million tonnes, including 178 million tonnes from aquatic animals and 36 million tonnes from phytoplankton, an increase of 3% over the previous record set in 2018 (FAO, 2022). Aquaculture's share of global production in 2020 was 122.6 million tonnes, composed of 87.5 million tonnes of aquatic animals and 35.1 million tonnes of phytoplankton worth a total of USD$ 281.5 billion (FAO, 2022). Furthermore, aquaculture plays an important role in the conservation of endangered species like sturgeon by allowing breeders to raise them outside of their natural habitats (Vasilyeva, Elhetawy, Sudakova, & Astafyeva, 2019). Sturgeon farming is a relatively new sector of aquaculture that is currently of great interest, as farmed sturgeon is the world's main provider of caviar in light of the dramatic decline in sturgeon fisheries and the rising demand for caviar worldwide (Bronzi & Rosenthal, 2014).

Acipenseriformes are a unique group of ancient aquatic animals that first appeared between 200 and 250 million years ago; today, they are the most primitive class of endangered vertebrates on Earth (Vasilyeva et al., 2019; Chandra & Fopp-Bayat, 2021). Two families, Acipenseridae (sturgeon) and Polyodontidae (paddlefish), are included in the order of Acipenseriformes. The family of Acipenseridae includes 4 genera, namely *Acipenser*, *Huso*, *Pseudoscaphirhynchus*, and *Scaphirhynchus* (Billard & Lecointre, 2001). In general, sturgeons dwelt in Northern Hemisphere reservoirs above the 30th parallel, including the Pacific, Atlantic, Mediterranean, and Black Seas, as well as rivers, lakes, and inland seas (Chandra & Fopp-Bayat, 2021). Historically, the wild sturgeon population had significant value because it supplied the world market with sturgeon products for many years before drastic fluctuations occurred in all major species. In 1977, the highest yield (32078 tonnes) of wild sturgeon was recorded (Bronzi et al., 2011). In the late 1980s, approximately 24000-26000 tonnes of Beluga (*Huso huso*), Russian sturgeon (*Acipenser gueldenstaedtii*), and stellate sturgeon (*Acipenser stellatus*) were captured annually in the Volga-Caspian region, which accounted for over 90% of the world's sturgeon production (Kokoza, 2004). However, subsequent FAO statistics on caviar removal from the Caspian Sea indicated that it was 2.1 tonnes in 2013, compared to 261 tonnes in 1992 (FAO, 2014).

In the majority of the last century, natural sturgeon populations have settled in the basins of the Sea of Azov, the Black Sea, and the Caspian Sea, with around 90% of global stocks concentrated in the Caspian Sea (Vasilyeva et al., 2019). Since the late 1980s, natural sturgeon populations have experienced a dramatic decline due to severe habitat degradation and overexploitation of both wild and artificially produced individuals for caviar production (Vasilyeva et al., 2019; Chandra & Fopp-Bayat, 2021: Brevé et al., 2022). During the period from 1985 to 2005, the sturgeon fishery was severely depleted due to a variety of factors. Politically, the collapse of the Soviet Union was accompanied by a sharp decline in the otherwise stringent enforcement measures governing this lucrative fishery; concurrently, the economic and social difficulties that coincided with this disintegration encouraged massive overfishing. In addition, fragmentation of the river (damming) and pollution exacerbated the environmental stress on the declining stocks. Moreover, the previous extensive stocking programs have decreased to their lowest level ever (Vasilyeva et al., 2019). Consequently, a four-fold decrease was observed in the number of wild sturgeon fish between 1992 and 1995, as experts confirmed that sturgeon numbers in the Caspian Sea decreased from 200 million to 50 million pieces and continued to decline, reaching a reduction of 90% in 2005 (Vasilyeva et al., 2019). At present, according to the International Union for Conservation of Nature and Natural Resources (IUCN), four Acipenseriformes species are now extinct, and 85% of the remaining 23 species are highly endangered (GAIN Report, 2014; WWF, 2017; Brevé et al., 2022).

As wild sturgeon numbers continued to decline sharply after the collapse of the Soviet Union, caviar production from sturgeon fisheries has reached zero, according to CITES quotas. This sharp fall in the number of sturgeons in nature coincided with rising global market demand for sturgeon products (meat and caviar), resulting in the emergence of sturgeon aquaculture, primarily for caviar production. The countries where sturgeon farming originated are those where sturgeon is naturally prevalent, such as Russia and Iran, along with members of the European Union and the USA, and sturgeon aquaculture is now prevalent in all six continents (Bronzi et al., 2019). The purpose of this work is to highlight the critical role that aquaculture plays in preventing the extinction of these unique fish, to examine the global expansion of sturgeon farming, to indicate the state of sturgeon fisheries renewal, and to provide a glimpse into opportunities for sturgeon aquaculture in Egypt.

Initiation of sturgeon aquaculture

Historically, sturgeons are ancient aquatic animals that live in littoral and inland waters and produce caviar, which is a gastronomic subtlety and is one of the most expensive products produced by wild animals for people all over the world; it is the unfertilized roe of sturgeon and paddlefish. Earlier, the world production of sturgeon products was sourced from sturgeon fishery, and caviar was produced only in the "river" and the coastal areas, particularly in Russia and the Caspian zone. However, with the subsequent dramatic declines in many sturgeon populations in the wild, scientists have undertaken attempts to breed and cultivate sturgeon in captivity, principally for caviar production. The history of sturgeon aquaculture dates back to 1869 when Russian academician Fyodor Ovsyannikov successfully conducted trials on artificial impregnation of sterlet caviar, and then this branch flourished during the subsequent period of the Soviet Union time. Within the years 1869-1915, Soviet scientists established the scientific foundation for controlled fertilization of sturgeon bleaching, as well as the development of progeny. In 1941, for the first time under controlled conditions, scientists used a suspension of the sturgeon pituitary gland as a hormonal excitant to conduct sturgeon gametogenesis. In the 1960s, Burtsev used a small cut into the ventral cavity to harvest caviar from sturgeon females in vivo, while Burtsev and others enhanced biotechnologies for mercantile sturgeon farming. Furthermore, scientists were able to obtain the hybrid "bester" for the first time in 1985, which became an important facility in sturgeon aquaculture throughout Russia (Vasilyeva et al., 2019). Studies conducted by Soviet scientists formed a large basis for subsequent experiments involving the growing of sturgeon in captivity in many places across the world, leading to the current global expansion of sturgeon farming.

Global growth of sturgeon aquaculture

The first FAO-recorded harvest of farmed sturgeon was in 1984, with an amount of 150 tonnes (Harris & Shiraishi, 2018). It gradually increased until the early 2000s, when it began to boom tremendously. With a production level of 51500 tonnes in 2011, the estimated global sturgeon yield from aquaculture exceeded the peak fishery production in 1977 by more than 73%. Keeping its upward trend, farmed sturgeon yield reached its peak in 2015 (129608 tonnes), an increase of more than 36% over 2014 and more than three times over 2010. After peaking in 2015, global cultured sturgeon production fluctuated before reaching an all-time high yield in 2021, as illustrated in Figure 1 (Bronzi et al., 2019; EUMOFA, 2021; FAO, 2023). By 2021, the global yield of

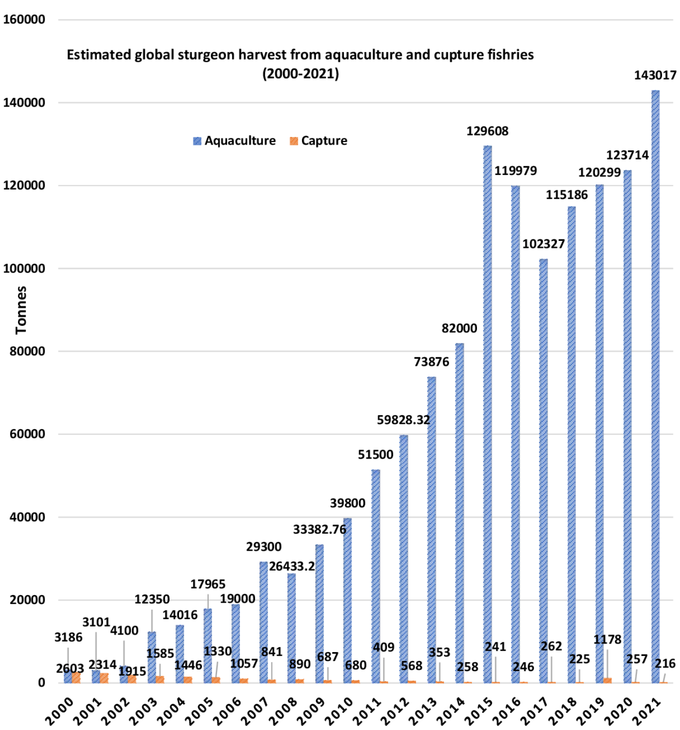

Figure 1. Estimated global sturgeon production from fisheries and aquaculture during 2000-2021. (Data from Bronzi & Rosenthal, 2014; EUMOFA, 2018 & 2021; Bronzi et al., 2019; FAO, 2023).

sturgeon peaked at 143234 tonnes, with 143017 tonnes originating from aquaculture and 216 tonnes sourced from fisheries (FAO, 2023). This was driven by China, with China's production accounting for more than 85% of global output in 2021 (FAO, 2023). The number of countries involved in sturgeon farming has been steadily increasing year by year. FAO (2015) indicated that the harvest of farmed sturgeon came from more than 38 countries embroiled in sturgeon cultivation, and that number increased to approximately 56 in 2017, and 80 in 2021 (FAO, 2015 & 2023; Bronzi et al., 2019). According to FAO statistics (2023), 144 countries contributed to sturgeon production in 2021 (aquaculture 80, and fishery 64) (FAO, 2023).

Over the past two decades, sturgeon aquaculture has experienced exponential expansion. According to the FAO, global production of sturgeon reached 4100 tonnes in 2002, half of which came from Russia and the rest of the European Union, and then tripled in 2003, when China's production began to rise. By 2021 China's production increased more than thirteen-fold between 2003 and 2021, from 9000 tonnes to nearly 121875 tonnes (EUMOFA, 2021; FAO, 2023). The world's largest producers of sturgeon in 2021 are China (121875 tonnes), Russia (5047 tonnes), Armenia (4300 tonnes), Iran (3145 tonnes), Vietnam (2660.2 tonnes), Italy (1252 tonnes), and the USA (1166.2 tonnes) (FAO, 2023). Among the Arab countries, the UAE contributed 65.13 tonnes to global sturgeon production (FAO, 2023). According to Bronzi et al. (2019), there are approximately 2329 sturgeon and paddlefish farms involved in sturgeon farming worldwide.

Global caviar production from aquaculture

Since the first kilograms of cultured sturgeon caviar came onto the market in the early 1990s, the harvest of farmed caviar production has exhibited an upward curve. In 2008, the estimated global production of caviar from aquaculture for all species was between 110 and 120 tonnes, harvested from 80 farms in 16 different countries. This shape has changed rapidly, with the majority deriving from at least six hybrids that are all cultivated in more than 30 countries, including some outside the natural range of sturgeons (such as South America) (Bronzi et al., 2011). Consequently, the estimated global caviar yield in 2012 was over 260 tonnes. This significant increase was intended to compensate for the lack of sturgeon fisheries. As demonstrated by Figure 2, global caviar output climbed steadily, peaking in 2019 at 592.74 tonnes before declining to 571.9 tonnes in 2020 (EUMOFA, 2018; Bronzi et al., 2019; FAO, 2022).

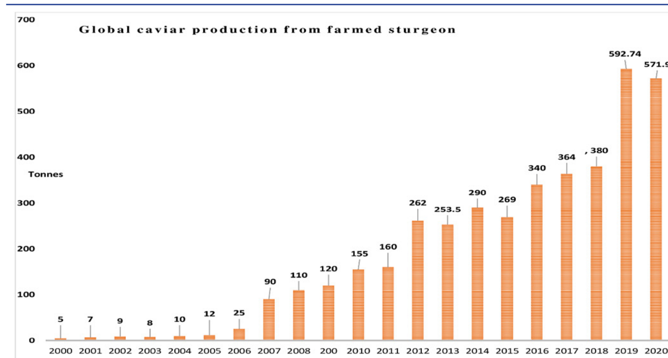

Figure 2. Estimated global caviar harvested from aquaculture sector during 2000-2020. Data retrieved from (Bronzi & Rosenthal, 2014; EUMOFA, 2018 & 2021; Bronzi et al., 2019; FAO, 2022).

China is the greatest producer of caviar in the world, accounting for more than a third (205 tonnes and 200 tonnes) of global production in 2019 and 2020, respectively (FAO, 2022). Denmark follows China as the second largest contributor to global caviar output with 60 tonnes, accounting for more than 10% of worldwide production, in 2020. After Denmark, came Russia (58 tonnes), Italy (55 tonnes), France (49 tonnes), Germany and Poland each had 18 tonnes, Armenia (15 tonnes), and Iran (12 tonnes) in 2020 (FAO, 2022). In addition, the Arab countries, represented by the Kingdom of Saudi Arabia, contributed 6 tonnes of caviar to global production in 2020 (FAO, 2022).

Global cultured species of sturgeons

The gap between the substantial commercial interest in sturgeon products and the limited availability of native sturgeon populations drives the global expansion of sturgeon farming. As a result, in 2017, 22 of the 27 sturgeon species (12 original and 10 hybrids) were farmed in more than 2329 sturgeon and paddlefish farms spread over 56 countries (Harris & Shiraishi, 2018). The most well-known original species for commercial cultivation are Siberian sturgeon (*Acipenser baerii*), Russian sturgeon, Beluga, Sterlet (*Acipenser ruthenus*), and some other species in regional dependence, such as Adriatic sturgeon (*Acipenser naccarii*) in Italy and White sturgeon (*Acipenser transmontanus*) in North America (Bronzi et al., 2019).

Regarding the pure species, the Siberian sturgeon, Adriatic sturgeon, sterlet, beluga, and white sturgeon are the pure forms that dominate global aquaculture for meat production, with 39.5%, 10.2%, 1.9%, 1.3%, and 1.1%, respectively. Siberian sturgeon, Russian sturgeon, white sturgeon, sterlet, Kaluga sturgeon (*Huso dauricus*), beluga, Adriatic sturgeon, and Stellate sturgeon dominate the global culture for caviar production, with quotas of 30.9%, 20.4%, 12.1%, 5.2%, 4.4%, 1.2%, 0.58%, and 0.47% (Bronzi et al., 2019).

In terms of hybrids, there are various hybrid forms around the world; however, the most common ones utilized in commercial farming are those that show the effect of heterosis, which allows for increased fish productivity in comparison to the original parental forms. The dominant hybrids utilized in meat production around the world are *Huso dauricus* × *Acipenser schrenckii* and *A. baerii* × *A. schrenckii*, which account for 35.6%, while additional hybrid forms (some of which have been named, while others have not) account for more than 10%. *Huso. dauricus* × *A. schrenckii* is the largest hybrid contributing to caviar collected from aquaculture (13.1%) globally. Other variants with more than an 11% share include *A gueldenstaedtii* × *A baerii*, H huso× A *ruthenus*, *A baerii* × *A gueldenstaedtii*, *A baerii* × *A naccarii*, and others (Harris & Shiraishi, 2018; Bronzi et al., 2019). Table 1 shows

Table 1. Distribution of cultivated sturgeon species and/or hybrids worldwide.

Acipenseriformes	Common name	Distribution
Subfamily Acipenseridae		
Genus Acipenser		
Acipenser baerii Brandt, 1869	Siberian sturgeon	Russia (Siberian rivers) & Kazakhstan
Acipenser gueldenstaedtii Brandt, 1833	Russian sturgeon	Russia, Kazakhstan & Black, Caspian, Azov seas
Acipenser ruthenus L., 1758	Sterlet	Russia, Romania & Eurasian countries
Acipenser stellatus Pallas, 1771	Stellate sturgeon	Caspian, Azov, Black, Aegean
Acipenser schrenckii Brandt, 1869	Amur sturgeon	Amur River (China)
Acipenser persicus Borodin, 1897	Persian sturgeon	Caspian Sea
Acipenser oxyrynchus Mitchill, 1815	Atlantic sturgeon	North American East coasts
Acipenser nudiventris Lovetzky, 1828	Ship sturgeon	Aral, Black, Caspian & rivers
Acipenser naccarii Bonaparte, 1836	Adriatic sturgeon	Adriatic Sea & tributaries
Acipenser fulvescens Rafinesque, 1817	Lake sturgeon	Great Lake, southern Canada
Acipenser dabryanus Dumeril, 1868	Yangtze sturgeon	Yangtze River system
Acipenser brevirostrum Le Sueur, 1818	Shortnose sturgeon	North American east coast
Acipenser transmontanus Richardson, 1836	White sturgeon	North American Pacific coasts
Acipenser sturio L., 1758	Common sturgeon	Baltic, N. Atlant., Medit., Black
Acipenser mikadoi	Sakhalin Sturgeon	Sakhalin, Japan Sea Rivers & Amur River
Genus Huso		
Huso dauricus Georgi, 1775	Kaluga sturgeon	China (Amur River system), Russia
Huso huso L., 1758	Beluga	Russia, countries around the Caspian & Black Seas, the northern part of Adriatic Sea (Po River).
Subfamily Scaphirhynchinae		
Genus Scaphirhynchus		
Scaphirhynchus platorynchus Rafinesque, 1820	Shovelnose sturgeon	Mississippi Missouri system
Family Polyodontidae		
Polyodon spatula Walbaum in Artedi, 1792	Paddlefish	Mississippi River (USA)
Psephurus gladius Martens, 1862	Chinese Paddlefish	Yangtze River system
Hybrids		
H. huso × A. Ruthenus	Bester	
A. baerii × A. Gueldenstaedtii	BAGU	
H. dauricus♀× A. schrenckii♂ or reversed cross		China, Russia
H. huso♀ × A. baerii♂		Russia, countries around Caspian Sea
A. baerii♀ × A. schrenckii♂ and reversed cross		
A. gueldenstaedti × A. Schrenckii		
A. naccarii × A. Baerii	AL, Baccarii	
A. stellatus × A. Ruthenus	Schipp	

Data retrieved fromBronzi & Rosenthal, 2014; Shen et al., 2014; Vasilyeva et al., 2019. In Russian.

the most common sturgeon species and/or hybrids used in aquaculture around the world.

At the state level, each country has its own variety of sturgeon hybrids; for example, in China, the most common hybrids employed in commercial aquaculture are *H dauricus*♀ × *A. schrencki*♂, *A. schrencki*♀ × *H. dauricus*♂, *A. baerii*♀ × *A. schrenckii*♂, and A. *schrenckii*♀ × *A. baerii*♂, accounting for 26% of the total output (Shen, Shi, Zou, Zhou, & Wei, 2014). In Russia, numerous hybrid forms and domesticated breeds are documented in the sturgeon polity registry. For instance, the following five domesticated breeds were listed in 1993: (1) Beluga by OJSC "Volgorechenskrybkhoz," Kostroma region; (2) Paddlefish by the fish breeding farm "Hot Key," Krasnodar region; (3) Russian sturgeon by the Federal Center of Fish Selection and Genetics, Leningrad Region; (4) Siberian sturgeon by the Konakovsky hatchery for sturgeon trade of the VNIRO Institute (http://vniroinfo.ru), Moscow region; and (5) Sterlet by the Konakovo hatchery for sturgeon trade, Tver region (Bogeruk, 2008). In addition, three hybrids (beluga x sterlet, called Burtsevsky bester, sterlet x bester, called Aksai bester, and Vnirovsky bester, beluga x bester, i.e., *Acipenser nikoljukini*) were registered in 2000 (Vasilyeva et al., 2019). With a 7% production share, one hybrid, Bester (*H. huso × A. ruthenus*), is the predominant form in Russian aquaculture (Vasilyeva et al., 2019).

Systems and technologies for sturgeon aquaculture

Various systems and techniques are applied in sturgeon farming around the world, depending on the country, location, climatic conditions, available water resources, the country's economic status, farmers, and so on. According to Bronzi et al. (2019), the flow-through method (FTM) and recirculating aquaculture systems (RAS) are the dominant two methods used in sturgeon aquaculture worldwide. FTM and RAS have a combined share of up to 68% in sturgeon farming around the world, with 36% for FTM, 21% for RAS, and 11% for a combined technology of FTM/RAS (Bronzi et al., 2019). Then there were cages and ponds, with 18% and 6%, respectively. However, the situation varies by state; for example, in China and Russia (the two world's top producers), cages account for roughly one-quarter and two-thirds of total output from farmed sturgeon in these countries, respectively. Furthermore, the pond-rearing method is widely used in Central and Western European countries, and the RAS is found all over the world, primarily in countries with limited water resources, unfavorable climatic conditions, and high levels of ecological emissions (Bronzi et al., 2019; Vasilyeva et al., 2019).

The culturing programs implemented to back up the natural sturgeon populations

Historically, the culturing programs that succeeded in reversing the declines of the natural population of sturgeon in the Caspian Sea date back to the late 1950s. Since the number of wild sturgeons in the Caspian and Azov Seas had begun to decrease at that time, a sturgeon breeding program was initiated. Soviet scientists managed to develop a technique for replenishing wild sturgeon populations through controlled reproduction. Using this technique, they were able to conduct the hormonal induction of the mature brooders in captivity, obtain eggs and sperm, perform artificial insemination, incubate the vivid fetus until it hatches, and then raise the larvae in tanks and/or ponds, aiming for fingerlings aged 1–1.5 months with an average body weight of 3–5 g to be released into the spawning rivers or sea estuaries (Milstein, 1982: Vasilyeva et al., 2019).

Since 1953, over 3 billion sturgeon fingerlings have been released into the Caspian basin (Figure 3). Four countries (Russia, Kazakhstan, Azerbaijan, and Iran) have contributed to this number; however, the majority (2.22 billion specimens, or 74%) of the total fingerlings, were produced by Russian hatcheries (Vasilyeva et al., 2019). In the lower Volga region, nine sturgeon hatcheries (7 in Astrakhan and 2 in Volgograd) were constructed for commercial aquaculture and release, along with two in Dagestan, two in Kazakhstan, three in Azerbaijan, and five controlled sturgeon hatcheries in Iran. The annual capacity of hatcheries to produce sturgeon juveniles (*Huso huso*, *Acipenser gueldenstaedtii*, *Acipenser nudiventris*, *Acipenser stellatus*, and *Acipenser ruthenus*) was 90–92 million. In the late 1980s and early 1990s, the release of sturgeon juveniles reached a peak value of 101 million pieces, with the USSR accounting for 90% of the total number released (Kokoza, 2004). In the Black Sea, Turkey has implemented programs to rehabilitate and protect sturgeon populations in Turkish waters since 1997 (Akbulut et al., 2001). Conservation and rehabilitation programs included six anadromous sturgeon species (*H. huso*, *A. gueldenstaedtii*, *A. sturio*, *A. nudiventris*, *A. stellatus*, and *A. ruthenus*) that entered the Kzlrmak, Yeşilrmak, Sakarya, and Çoruh rivers for spawning, and the majority of the sturgeon fingerlings released were in the Yeşilırmak River and Sakarya between 2001 and 2013. (Akbulut et al., 2001; Zengin, Tiril, Dağtekin, Gül & Eryildirim, 2010; Tiril & Memiş, 2018).

In general, the controlled propagation strategy is based on utilizing mature adult broodstock collected from the wild to produce sturgeon progeny in hatcheries following adaptation to controlled conditions. However, due to a severe scarcity of wild broodstocks taken from nature to operate hatcheries and pro-

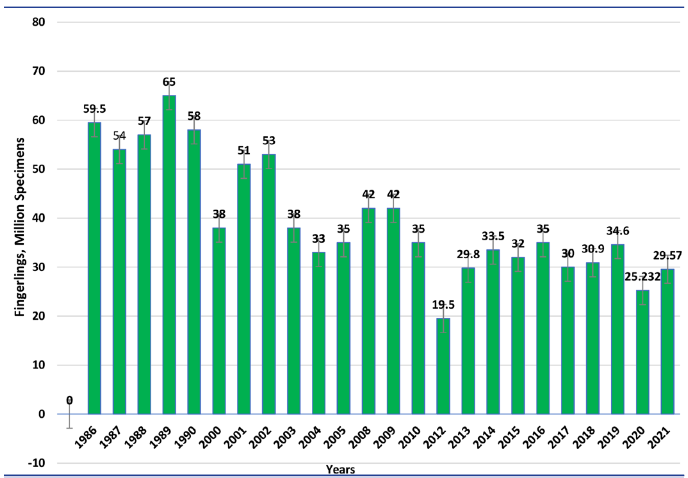

Figure 3. The figure of sturgeon juveniles released into the Volga-Caspian basin within the period of 1986-2021. Retrived from Rosrybolovstvo activities and tasks 2009-2021: https://fish.gov.ru/about/kollegiya-rosrybolovstva/.

duce sturgeon seedlings, it has begun to develop a sturgeon broodstock from overripe adult fishes raised from hatchery fry (Kokoza, 2004; Vasilyeva, Naumov, & Sudakova, 2015).

Global marketing of sturgeon caviar

Focusing on the global trade of wild sturgeon products (meat and caviar), until 1991, the majority of the world's sturgeon catch and caviar harvest came from Russian fisheries, which supplied up to 28000 tonnes of sturgeons and up to 2000-28000 tonnes of caviar, while the annual world export market for caviar was over 570 tonnes at that time (Vasilyeva et al., 2019). The total global capture of sturgeons in 2021 was 216 tonnes. Except for Uzbekistan (quota of 20 living specimens of Amu Darya Sturgeon *Pseudoscaphirhynchus kaufmanni* in 2017), no quotas for wild captures of *Acipenseriformes* spp. have been reported since 2011. Azerbaijan supplied all caviar from wild Russian sturgeon between 2010 and 2015 (Harris & Shiraishi, 2018). Furthermore, the top two exporting countries for wild caviar were the United States (40 tonnes) and Germany (19.4 tonnes), while the top three species producing wild caviar were American Paddlefish *Polyodon spathula* (48.011 tonnes), Russian sturgeon (6.030 tonnes), and shovelnose sturgeon *Scaphirhynchus platorynchus* (5.416 tonnes) (Harris & Shiraishi, 2018; EUMOFA, 2018).

The CITES trade statistics showed that reported caviar (re) exports (from wild and aquaculture) totaled 1599 tonnes between 2000 and 2015, and exhibited a general decrease during that time, from 229 tonnes in 2000 to 108 tonnes in 2015. Aquaculture caviar exports increased throughout the same period of time, reaching 102 tonnes in 2015, accounting for 95% of total trade by weight (Harris & Shiraishi, 2018 EUMOFA, 2018). During this period, the majority of direct exports were caviar harvested from aquaculture, but 66% of USA exports were wild-derived caviar (Paddlefish and Shovelnose Sturgeon). Between 2010 and 2015, the top three species of farmed sturgeon that produced caviar for the global market were Siberian sturgeon, a hybrid *Huso dauricus* x *Acipenser schrenckii*, and Russian sturgeon. Figure 4 shows the main aquacultured sturgeon species contributing to sturgeon caviar exports (Harris & Shiraishi, 2018; EUMOFA, 2018).

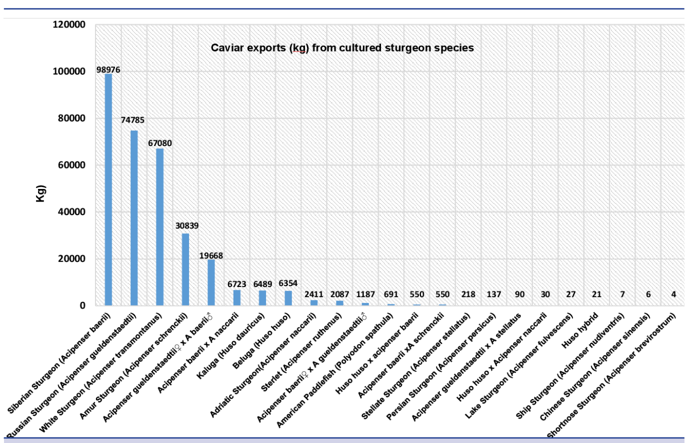

Figure 4. Cultured sturgeon species contributing to sturgeon caviar exports. Data retrieved from (Harris & Shiraishi, 2018; EUMOFA, 2018).

According to FAO statics (2022), the exported amounts of caviar accounted for 762.21 tonnes in 2020. There was a quota for about 52 countries that contributed to the export of caviar in 2020. Denmark topped the exporting countries with about a 30% share of global caviar exports, followed by China with a share of about 16% of global caviar exports (FAO, 2022). There are quotas for UAE caviar exported in 2019 (10.55 tonnes) and in 2020 (0.01 tonnes) (FAO, 2022). Figure 5 illustrates the major exporting countries of sturgeon caviar in 2020 (FAO, 2022). In 2020, Egypt imported sturgeon caviar (net product) with an amount of 14.34 tonnes from Denmark, Norway, Sweden, Thailand, the UAE, and others, while it imported caviar and caviar substitutes with an amount of 15.15 tonnes from China, Denmark, Norway, and Sweden (FAO, 2022).

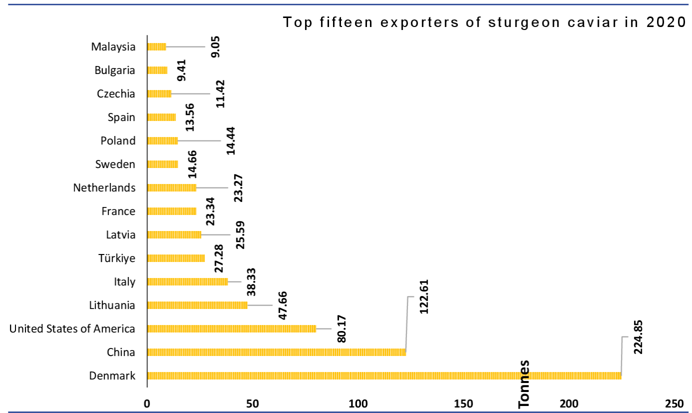

Figure 5. The leading exporting countries of sturgeon caviar in 2020. (Data retrieved fron FAO, 2022).

Prospects for caviar production

According to FAO statistics, the harvest quantity of farmed sturgeon has increased substantially, from 19000 tonnes in 2006 to 105000 tonnes in 2016. Sturgeon production is thought to consist of early male harvesting within 3-4 years of growing, as well as raising females for caviar production. Taking into account (on a global basis) that the average cycle time necessary to create caviar is 8 years from hatch to first reaping of ripe sturgeon, the 340 tonnes of caviar harvested in 2016 resulted from a world sturgeon production of 26000 tonnes (FAO production estimate 2007/2008). In 2017, global production was four times more than in 2007/2008, reaching 103000 tonnes. According to Harris and Shiraishi (2018), when these sturgeons reach maturity, the production of caviar can reach a thousand tonnes if the same caviar/sturgeon ratio as described above for sturgeon production in 2017 is used. This amount is supported by other literature, with future production predictions ranging from 500 to 2000 tonnes (Sicuro, 2018).

The global caviar trade market recorded a growth rate of 6.7%, with an estimated market size of US$76123 million in 2022, and a projected market value of US$ 86764 million in 2023. Furthermore, the caviar trade industry is predicted to rise at a 14.43% CAGR to reach a value of US$ 223885 million by 2030 (Global Caviar Market, 2022; Market Research Future, 2023). This raises concerns about the possibility of greater supply versus demand, which means reduced pricing and profitability, particularly given the constant expansion in Chinese caviar production, which has already resulted in considerable drops in the worldwide caviar price (EUMOFA, 2018 & 2021). Substandard quality control and the need to format due to increasing consumer demand for caviar production are the key challenges encountered by aquaculture companies throughout the caviar-trading encounter (Sicuro, 2018).

Prospects for sturgeon aquaculture in Egypt: an overview

Egypt is located in the Middle East region, which has around 186 sturgeon farms, accounting for 8% of all sturgeon facilities globally (Bronzi et al., 2019). The United Arab Emirates and Saudi Arabia are two of the main countries in this field that are near Egypt and have achieved exceptional success in sturgeon aquaculture. In comparison to these countries, Egypt has a high potential due to significant advantages such as moderate climatic conditions and well-trained and inexpensive labor. Egypt also possesses natural fresh, marine, and brackish water resources, such as the Nile and delta, the Mediterranean and Red Seas, open and closed lakes, and oases. Furthermore, huge aquifers that run the length of the country supply suitable water for aquaculture in general and sturgeon farming in particular. These characteristics are significantly superior to those of the other countries indicated, which are currently involved in successful sturgeon farming.

Egypt has the biggest aquaculture production share in the Mediterranean region, with 31%, followed by Turkey (29%), Italy (21%), and Greece (14%) (FAO, 2019). Furthermore, Egyptian aquaculture is the largest in Africa, accounting for more than 67.5% of the continental industry. In 2020, Africa contributed 2354000.3 tonnes to worldwide aquaculture of all farmed species, accounting for 1.92% of total global aquaculture (FAO, 2022). Egypt's aquaculture ranked sixth in the world in 2020, with 1591900 tonnes (FAO, 2022). On a global scale, Egypt is the leading producer of mullet (family *Mugilidae*) with 351197 tonnes (93.8%) of global mullet production, totaling 374072 tonnes, in 2021 (FAO, 2023). Furthermore, with 954154 tonnes, Egypt is the third-largest producer of Nile tilapia (*Oreochromis niloticus*) after China (1241410 tonnes) and Indonesia (1172633 tonnes) (Geletu & Zhao, 2022). After Turkey and Greece, Egypt is the third largest producer of European seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*) (Lotfy et al., 201: Abdel-Rahim et al., 2023). Egypt produced 33245 tonnes of European seabass and 42743 tonnes of gilthead seabream in 2021, while the world's two largest producers, Turkey and Greece, produced 155151 tonnes and 51231.8 tonnes of European seabass and 133476 tonnes and 66890.8 tonnes of gilthead seabream, respectively (FAO, 2023).

Egypt's aquaculture industry is diverse in terms of farmed (fresh, brackish, and mariculture) species and culture systems, including governmental and private farms, cages, aquaculture in rice fields, semi-intensive, and intensive aquaculture systems (GAFRD, 2016 & 2020). Aquaculture characteristics include diversity and large scale, as well as current modernization through the construction of mega-projects implemented by the country in recent years, such as: (a) the national project for mariculture in the Suez Canal, with a potential target production capacity of 150000 tonnes/year; (b) the Ghalion aquaculture project in Kafr El-Sheikh governorate on a total area of 2000 hectares, including 453 marine fish ponds, 626 shrimp ponds, 186 nursery ponds, and a marine hatchery; and (c) the national project for developing East Port Said, over an area of 10,920 hectares with a potential annual target production of 50000 tonnes (GAIN Report, 2016). All of these factors contribute to and boost the possibility of successful sturgeon farming in Egypt.

Currently, Egyptian authorities, legislative bodies, and research institutions are working to pass legislation that will make it easier for investors and international experts to collaborate with Egypt in this field. Restrictions have been discussed, focusing on the environmental and disease-controlling aspects of non-endemic species, along with continuous monitoring by specialized research and supervision bodies. Moreover, the Egyptian authorities are very open to introducing new species of fish and crustaceans. The non-endemic aquatic species that have recently entered Egypt, such as the Basa fish (*Pangasius sp.*), and Whiteleg shrimp (*Litopenaeus vannamei*), have become vital species in the Egyptian aquaculture industry (Kaleem & Sabi, 2020).

With the beginning of sturgeon cultivation in Egypt, there are three candidate species with rapid growth and rapid reproductive maturation in captivity. The first is Sterlet sturgeon, a freshwater, brackish, and demersal fish with a maximum weight of 16 kilograms, a maximum length of 1.25 meters, and a maximum lifespan of 25 years. They consume benthic organisms, including crustaceans, worms, and insect larvae. Females reach puberty at the age of four, ovulation occurs between mid-April and early June, and they lay between 15,000 and 44,000 eggs at optimum water temperatures of 12 to 17 °C (Gesner, Freyhof, & Kottelat, 2010). The second candidate species is Siberian sturgeon. Due to its easy reproduction, rapid growth, and lack of pathological issues, Siberian sturgeon is a better candidate for aquaculture than other species. It is a freshwater, brackish, and demersal fish that typically weighs up to 65 kg and lives up to 63 years, with a maximum recorded weight of 210 kg and length of 2 meters. In the environment, benthic organisms such as crustaceans and chironomid larvae comprise the food chain. Females reach sexual maturity at five years of age in captivity. They spawn in June-July with eggs measuring 3.0-3.6 mm, newly hatched larvae measuring 10-12 mm in length, and an incubation period of approximately 16 days at 10-15°C (We et al., 2011; Williot, Nonnotte, Vizziano-Cantonnet, & Chebanov, 2018). The third candidate species is Russian sturgeon: its farming represents a significant portion of global sturgeon aquaculture due to its superior meat and caviar quality among all sturgeons, with the exception of beluga caviar, which has a more exquisite flavor and higher nutritional value. This species is an anadromous euryhaline fish that is endemic to the Black, Azov, and Caspian Seas and migrates into the river systems that drain into these seas to reproduce. This species lives up to 47 years, achieving a body weight of roughly 115 kg and a length of 236 cm by the age of 7 years in RAS, whereas prototypes can mature in the fifth year (Elhetawy et al., 2020). They consume benthos (mollusks, crustaceans, worms, small fish-bulls, and sprats) and spawn between mid-May and early June at water temperatures between 8 and 15 °C. Individual fecundity ranges from 50 to 600 thousand eggs and can reach 1 million on occasion (We et al., 2011; Aquaculture Russia, 2023).

The use of these three species in the development of the sturgeon aquaculture industry will allow us to generate revenue from sturgeon meat by the end of the second year of cultivation, sturgeon caviar by the fourth year with sterlet, and sturgeon caviar by the fifth year with sterlet, Siberian sturgeon, and the best specimens of Russian sturgeon. In addition, other species with a high economic value for meat and caviar, such as beluga and Sevruga, will be introduced progressively. Furthermore, each of these native species has hybrids with others; hence, hybridization by systematic research on the crossing of sturgeon chromosomes may lead to the development of suitable varieties for Egypt's conditions, as has been done in China and Russia (Elhetawy et al., 2020).

Sturgeon aquaculture in Egypt requires the use of cutting-edge technology such as RAS, which will technically improve and modernize the aquaculture industry. The RAS and ponds (concrete and earthen) with groundwater utilization are the most convenient sturgeon-rearing technologies for Egyptian conditions. RAS allows for continuous growth throughout the year under completely controlled conditions, whereas ponds allow fish to grow in natural conditions, which improves the quality of meat and caviar produced and considerably reduces production costs (Elhetawy, Sudakova, Anokhina & Vasilieva, 2018). With the application of a combined RAS/pond technology, sturgeon farming could achieve tremendous success and generate substantial revenue. In the RAS system, sturgeon will grow for 7-8 months (during spring and summer, when environmental conditions are not ideal for sturgeon growth), and then continue to grow in reservoirs for the remainder of the year. Table 2 shows the water quality requirements for sturgeon growth using different culture methods (Vasilyeva et al., 2010).

The Northern region of Egypt, including the Nile Delta and Siwa Oasis, is most suited for creating sturgeon farms. The Nile Delta and Siwa Oasis's climatic conditions and groundwater quality are ideal for promoting the growth of sturgeon with the use of the RAS/ponds technology. The average daily temperature in the Delta is between 17 and 20 ° C, while the maximum temperature is between 26 and 34 ° C and the lowest is between 6 and 13 ° C (Abd-Elaty, Abd-Elhamid, & Negm, 2018; Negm, Sakr, Abd-Elaty, & Abd-Elhamid, 2019). The Siwa Oasis has a maximum temperature of 16.4 - 36 ° C (January - July) and a minimum temperature of 7.3 - 23.3 ° C (January - August), with an average daily temperature of 12.1 - 29.9 ° C (Climate-Data.Org).

In 2003, the gross annual freshwater abstraction from groundwater from the Nile Delta accounted for 2.0, 0.6, and 0.9 billion cubic meters (BCM) for the eastern, middle, and western regions, respectively (Abd-Elaty et al., 2018; Negm et al., 2019). The total groundwater prospect for each of the three zones (Western, Middle, and Eastern Delta) was calculated to be 1.2, 2.4, and 0.71 BCM per annum, respectively (Negm et al., 2019; Negm, 2019). The south and central regions of the Nile Delta have significant groundwater potential, where aquifer features (semi-confined) and recharge form and continuity (surface Nile water) allow for the extraction of huge volumes of high-quality groundwater from shallow depths. The salinity ranges from 0.296 to 0.810 g/l, with an increase to more than 5 g/l in the North Delta, while the pH ranges from 6.72 to 8.65 (Abd El-Fattah, 2014).

In the Siwa Oasis, freshwater is distributed throughout the oasis in the form of a significant number of wells and eyes (up to 200 eyes), from which 190 thousand cubic meters of water flow daily and are used for irrigation, drinking, bottled natural water, and treatment. Groundwater water may be divided into three major groups: fresh samples have been discovered in the Nubian sandstone aquifer, brackish samples are found in the fractured dolomite limestone aquifer, and saline samples are found in the

Table 2. Water quality requirements for sturgeon rearing.

Parameter	Ponds	Cages	RAS
Water temperature	19-24	12-24	18-24
Oxygen concentration, mg / l	6.0-8.0	8.0-9.0	6.0-10
Smells, tastes	Water should not have any odors or taste		
Transparency, m	Not less than 1.5		
Suspended solids, g / m^3	>25	>25	>10
Permanganate oxide, mg O_2 / m^3	>15	>10	>15
Bichromate, mg O_2 / m^3	>50	>30	>50
pH	7.2-8.5	7.5-8.5	7.0-8.0
Carbon dioxide, g / m^3	Not more than 10.0	-	-
Dissolved ammonia, g / m^3	>0.05	-	-
Ammonium ion, gN / m^3	0.5	0.5	2.0-4.0
Nitrite –ion, gN / m	0.01	0.01	0.1
Nitrate ion, gN / m^3	2.0-3.0	2.0-3.0	>60
Phosphate ion, g / m^3	0.1	0.1	0.3
Total Iron, g / m^3	0.5	0.5	-

Data retrieved from Vasilyeva et al., 2010. In Russian.

broken dolomite limestone aquifer. The salinity of the water ranges from 0.1688 g/l to 7.4728 g/l, with pH values ranging from 6.9-7.5 (Abo EL-Fadl, Wassel, Sayed, & Mahmod, 2015).

In these two locations, using RAS or the combined RAS/Ponds technology in the cultivation of the aforementioned species, Egyptian authorities may conduct the necessary feasibility studies and then launch an ambitious sturgeon aquaculture program in Egypt. Feasibility studies should contain short, medium, and long-term strategies for developing the project and introducing new sturgeon species with worldwide economic significance. The establishment of laboratories is required to perform experiments and scientific research in order to continuously promote farming techniques.

CONCLUSION

In the past quarter century, aquaculture has helped prevent the extinction of sturgeon. Controlled sturgeon reproduction is crucial for replenishing natural resources and operating sturgeon aquaculture to meet growing caviar demand. Controlled reproduction is needed not only to replenish natural populations, but also to preserve genetic diversity. To date, sturgeon aquaculture has contributed to the conservation of these species and compensated for the relative lack of caviar from wild resources by supplying farmed products to the global market. Only through sustainable aquaculture can these distinct, ancient species be preserved for future generations. In comparison to other countries in the region, Egypt has tremendous potential to successfully start sturgeon farming. Sturgeon aquaculture in Egypt will grow and modernize the aquaculture business by utilizing current technologies and increasing aquaculturists' efficiency. Furthermore, it will maximize groundwater utilization, generate new urban settlements, and provide an extra source of income to preserve hard currency, among other benefits. Furthermore, because Egypt is the northern entrance to Africa, the introduction of sturgeon aquaculture in Egypt would motivate many other nations in the region to take part in the business, which will be reflected in the global extension of its farming area and, ultimately, its wealth. Finally, the purpose of this review was to highlight the global importance of sturgeon farming and provide an overview of the potential opportunities for sturgeon farming in Egypt as a source of information for Egyptian decision-makers and fish producers. More in-depth research is needed to investigate, evaluate, and establish the basic guidelines for this industry.

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