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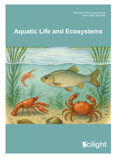

Review

Advances in Sturgeon Nutrition for Sustainable Aquaculture

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Abstract: Sturgeon aquaculture is one of the rapidly advancing sectors globally. For sustainable production and growth, it is essential to understand the nutritional requirements. This review presents ancient knowledge and recent advances on the dietary requirements of sturgeon. It aims to critically evaluate the progress and innovations over the past 25 years. The review synthesizes key findings from published papers and journals, highlighting sturgeon dietary requirements, alternative feed ingredients, commercial and functional feeds, and feeding strategies crucial to achieving economic viability and sustainability in sturgeon farming. It showcases the transition from fishmeal diets to alternative protein diets, aiming to minimize environmental impact and improve economic viability. It also discusses the integration of sustainable frameworks, such as the circular economy, One Health, and AI technology. Some research gaps include species-specific nutritional requirements, digestibility studies, the long-term impact of alternative protein diets, and the integration of AI technologies to optimize the sustainability and productivity of sturgeon aquaculture.

Keywords: alternate proteins; functional feed; sustainability; circular economy; precision feeding; one health; artificial intelligence

1. Introduction

Sturgeon are ancient and majestic fish that have existed for over 200 to 250 million years. This species has a long maturation period and typically survives 60 to 70 years. Sturgeon belongs to the family Acipenseridae, which comprises 27 species, out of which 25 are true sturgeon, while two belong to the paddlefish family. It is known for its luxurious delicacy, 'Caviar', and high-quality meat, due to which different sturgeon species are now farmed around the world [1–3]. Hung [4] claimed that sturgeon aquaculture has experienced worldwide growth over the past few decades, with potential applications in economics, ecology, recreation, and aquaculture. Zarantoniello et al. [5] stated that the suitability of sturgeon aquaculture was attributed to its rapid growth, stress resistance, favourable production efficiency, advances in nutrient digestibility, and adaptation to farming conditions. Additionally, this shift from capture fisheries to aquaculture improved food security and human nutrition while protecting natural stocks and reducing illegal wildlife trade. Due to overexploitation and habitat destruction, it is listed as an endangered species under the International Union for Conservation of Nature and Natural Resources (IUCN) Red List [6].

The first farmed sturgeon harvest was 150 tonnes in 1984 [7], and production gradually increased until the early 2000s, after which it experienced a steady surge (Figure 1). Sturgeon aquaculture was primarily driven by increasing consumer demand and the overexploitation of wild-sourced sturgeon. Data from EUMOFA [8] and FAO [9] indicate that the production peaked at 129,608 tonnes in 2015, with inevitable fluctuations in the following years due to environmental changes and fishing practices, and again reached up to 143,234 tonnes in 2021, with 143,017 tonnes from aquaculture and only around 216 tonnes from wild fisheries (Figure 2). Similarly, caviar production showed a gradual rise from 2017 onwards, with the highest recorded in 2019 (Figure 3). Reports [9] suggest that that China accounted for the highest production, contributing more than 85% of the global sturgeon farming, followed by Russia, Armenia, Iran, Vietnam, Italy, and the USA (Figure 4).

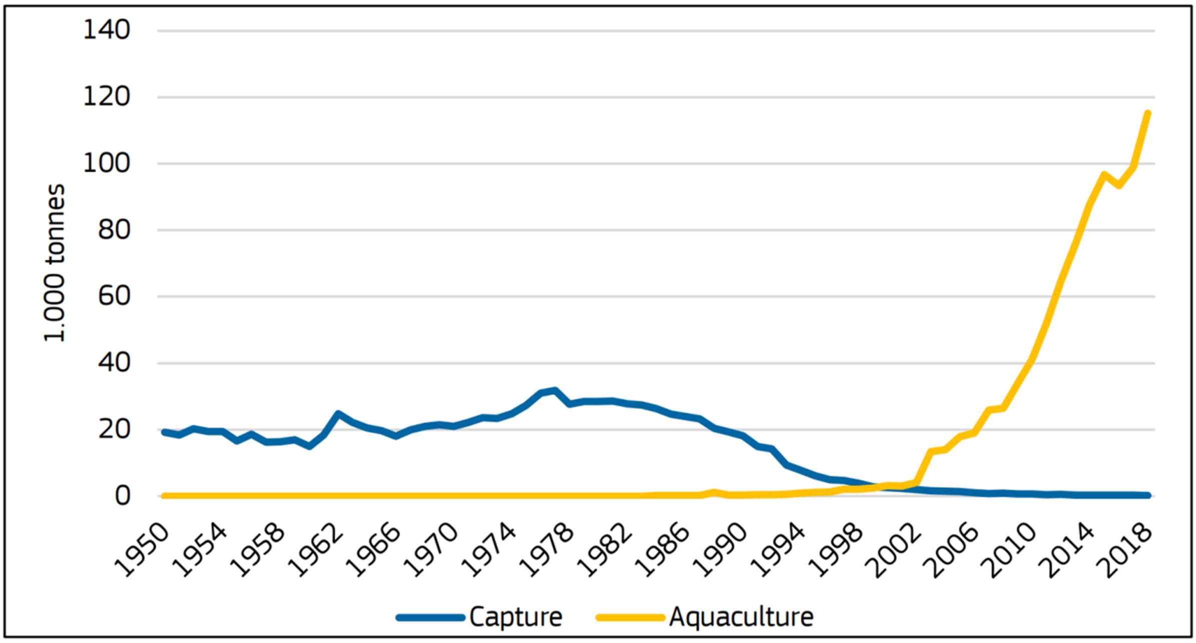

Figure 1. Sturgeon aquaculture vs capture fisheries. Data from EUMOFA 2021 [7].

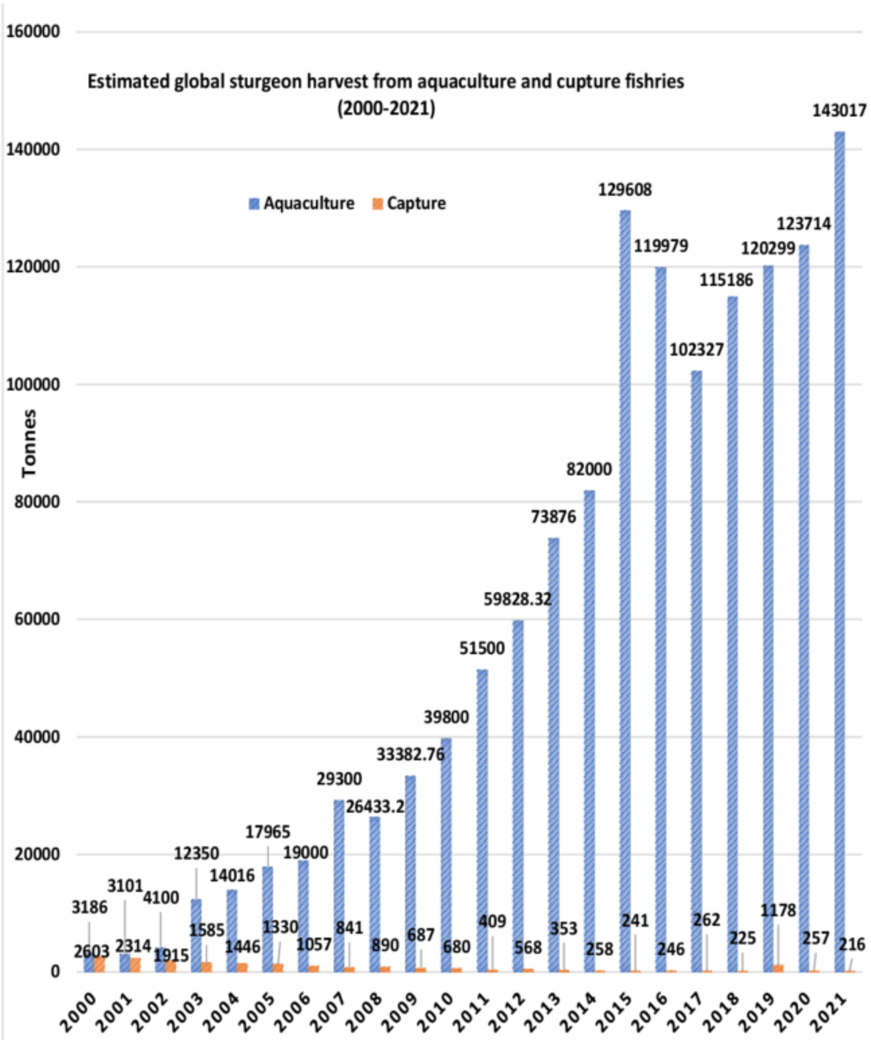

Figure 2. Global sturgeon production from fisheries and aquaculture during 2000–2021. Data from [7–11].

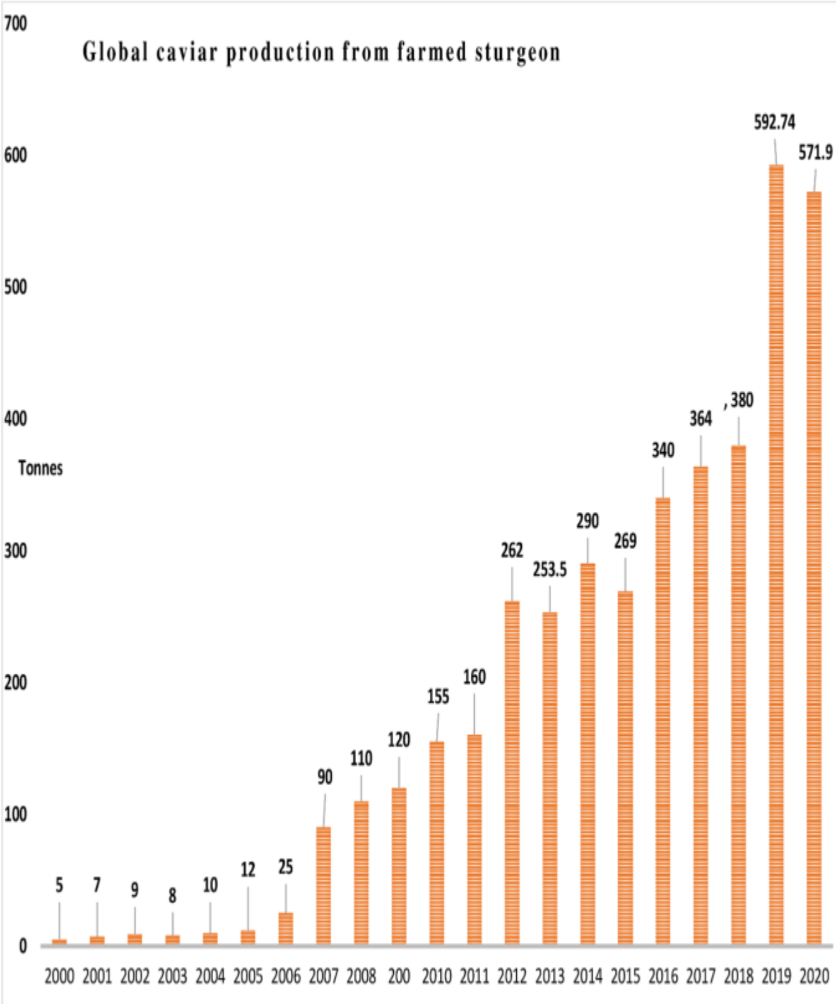

Figure 3. Global caviar production from the aquaculture sector during 2000–2020. Data from [7–11].

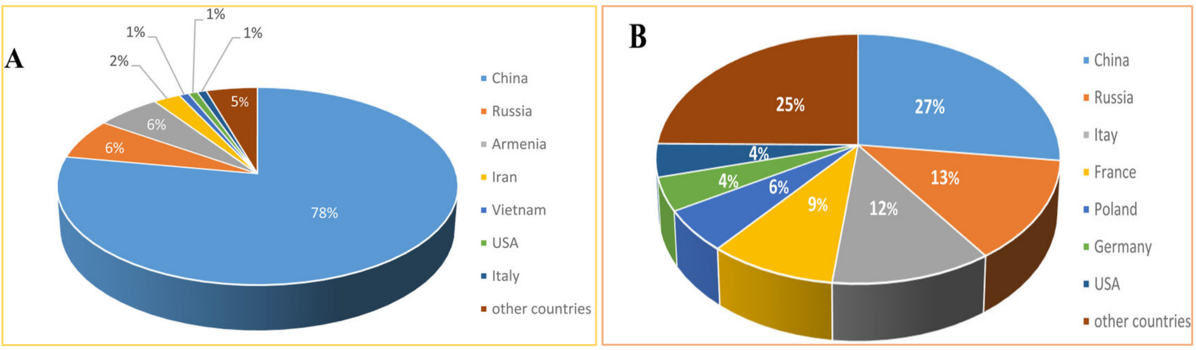

Figure 4. Countries leading in sturgeon (**A**) and caviar (**B**) production. Data from [9].

Although sturgeon aquaculture is increasing worldwide, several challenges must be addressed to ensure its long-term sustainability and continued development. Among the challenges, nutrition stands out as a critical bottleneck. Prabu et al. [12] stated that nutrition plays a crucial role, influencing factors such as growth, health, product quality, production costs, and environmental sustainability. It is necessary to understand the nutritional requirements of sturgeon to develop a balanced diet and appropriate feeding practices. This will help to improve nutritional expertise and develop cost-effective diets. Long et al. [13] stated that the formulation of a diet is crucial for sustainable fish production, as it will directly impact the growth performance and health of the fish. Correctly formulated sturgeon feed will enhance the food digestibility, metabolism and immune system. For sturgeon, it is imperative as it can influence the quality of caviar and meat, which is vital for market success. Key feed ingredients, such as fishmeal, are in limited supply, making it necessary to consider alternative protein sources, including plant-based proteins and insect meals. Additionally, Kolman and Kapusta [14] highlighted that the availability of raw materials, such as soybean meal and cereals, is becoming challenging due to price fluctuations.

This will help reduce reliance on wild stock to preserve aquatic ecosystems and support sustainable farming methods. This involves the use of readily available raw materials, requires minimal imports, has low costs, and offers potential for large-scale production. Pailan and Biswas [15] highlighted that feed costs account for nearly 50% of variable costs, which affects returns on investment. Therefore, as sturgeon aquaculture is a long-term investment, it is crucial to develop and use sustainable aquafeeds to meet the growing demand for sturgeon products.

Though there have been several review papers including [4,16] giving an insight into the sturgeon nutrition, this review provides a wider understanding of the evolution of sturgeon nutrition with recent advances including the application of sustainable frameworks such as circular economy and one health. This paper provides a comprehensive perspective addressing the current challenges, emerging technologies and future directions to enhance production efficiency and sustainability in sturgeon aquaculture. The primary objective of this review paper is to examine the significance of nutrition in sturgeon aquaculture, specifically its direct impact on growth, reproduction rates, immunity, and product quality. As a unique fish with a long maturation and gestation period, sturgeon requires optimized dietary formulations and the development of nutritional strategies to ensure it becomes a sustainable and profitable aquaculture species. This review will focus on research published over the last 20 years, highlighting key achievements in sturgeon nutrition. Additionally, it will provide a glimpse into the basic nutrient requirements and highlight improvements in nutritional aspects to enhance growth performance, sustainability, and profitability in sturgeon farming.

2. Materials and Methods

This study was conducted to provide a brief overview of the history and current knowledge, including research gaps in sturgeon nutrition. The review encompassed papers published from 2003 to 2025 on sturgeon nutrition, all written in English. Major database used included Google scholar, PubMed, ScienceDirect, Springer, and google searched relevant articles using the keywords like 'sturgeon nutrition', advances in sturgeon feed', 'Sturgeon feed ingredients', 'Sturgeon nutritional requirements', 'sturgeon byproducts', 'circular economy in aquaculture', 'One health in aquaculture' and 'Artificial intelligence in sturgeon farming'. Relevant articles were selected that provided core information on dietary protein and amino acid requirements, alternate protein diets, commercial diets, functional feed additives, feeding strategies and emerging technologies for sustainable sturgeon farming. Papers and articles that addressed recent advances, such as AI integration and the reuse of sturgeon by-products, were also highlighted. The EndNote library was used for in-text citations and referencing throughout the manuscript. In total, around 65 sources were reviewed and studied including peer-reviewed papers, book chapters, and published reports, such as the FAO Sturgeon Hatchery Manual, which were incorporated to provide a broader understanding of early and recent advances in sturgeon diets. Each article was thoroughly revised, and the key points were pooled in this paper to present the evolution of sturgeon nutrition for sustainable aquaculture.

3. Understanding the Basic Nutritional Requirements for Sturgeon

The nutritional component of sturgeon feed consists of both macronutrients and micronutrients. It requires high-energy diets containing approximately 40–50% crude protein, 12–20% crude fat, and 18–22 Kcal of energy [17]. Initially, salmonid feed was used because sturgeon farming was not yet well established, and its nutritional requirements were not well understood. Since salmonid diets yielded sufficient production, specialized research on sturgeon nutrition was not conducted until the late 2000s. Sturgeon has distinct morphological and physiological characteristics that differ from those of other fish [18]. It has a cartilaginous skeleton, a gastric digestive system, and a reduced enzymatic capacity, combined with slow growth and late sexual maturity, which necessitate highly digestible, protein-rich diets [19].

The studies by Mohseni et al. [20] and Guo et al. [21] suggested that the optimal crude protein level ranged from 37% to 40.5%, depending on the species and life stages. Diets rich in protein ensure the sufficient availability of amino acids required for tissue development, immune system function, and metabolic maintenance [4]. Elhetawy et al. [22] reported that sturgeon have increased requirements for specific amino acids, such as lysine, leucine, arginine, and methionine, but remain under-researched for each species. Hung [4] and Pelic et al. [23] stated that the optimal fat requirement for sturgeon depends on various factors, including species, life stages, sources, diet formulation, and environmental conditions. According to Li et al. [24], this is significant because fish may not maintain optimal growth at high fat levels, as excess fat can lead to reduced feed intake and metabolic disorders resulting from fat accumulation and an abnormal oxidative status. Sturgeon is known to use less carbohydrate, making protein and lipid more efficient sources of energy. Research conducted by Hung [25] on white sturgeon (*Acipenser transmontanus*) revealed glucose and maltose tolerance, resulting in hyperglycemia, indicating poor carbohydrate metabolism. A recent study by Liu and Naganuma [26] examined metabolomic profiles of bester sturgeon (Acipenser Hybrid) and revealed that amino acids and fatty acids were utilized, whereas carbohydrates remained unchanged. Thus, it is essential to determine the nutritional requirements, digestibility, and optimal nutrient balance necessary to achieve maximum growth, high feed efficiency, and the production of high-quality meat and caviar.

In sturgeon farming, digestibility and feed conversion ratio (FCR) are essential metrics that help determine how effectively the fish utilizes feed for growth. Optimizing the FCR is crucial for minimizing feed costs and managing the waste produced. Sturgeon that was initially fed with salmonid diet were found to have higher FCR values of 1.7 to 2.4 [27], indicating less efficient feed utilization. In contrast, sturgeon that were fed with sturgeon-specific diets provided a lower FCR values of 1.1 to 1.3 [4], indicating efficient feed utilization. This emphasized the need for sturgeon-specific diets to enhance the sustainability of sturgeon aquaculture.

4. Alternative Protein Sources: A Recent Transition in Sturgeon Aquaculture

Fishmeal is the primary source of protein for carnivorous fish due to its high protein levels, palatability, and digestibility [28]. Nonetheless, its higher cost and limited availability have led to the exploration of alternative protein sources. Ameixa [29] claimed that, due to the limited availability of fishmeal, scientists and researchers are developing unique and unconventional feeds, such as algae, processed animal protein, single-cell proteins, and insect meal. Some of the commonly utilized plant-based proteins included soybean meal, wheat gluten, and corn gluten, which helped reduce dependency on fishmeal. Other animal products, such as poultry byproducts, hydrolyzed feather meal, and blood meal, also provided a viable alternative to fishmeal. Insect meal and algal products exhibit immunostimulatory properties and contain functional compounds that enhance fish health, resistance to diseases, and advanced antioxidant status when compared to fishmeal [30]. Plant proteins, such as soybean meal and wheat gluten, offer a balanced amino acid profile and higher digestibility, making them a sustainable and cost-effective alternative to fishmeal [31]. Additionally, a combination of alternative protein sources, rather than a single source, improved fish growth and health. Some experimental trials on Amur (*Sinosturio schrenckii*) and Siberian sturgeon (*Acipenser baerii*) showed that using multiple protein sources increased the likelihood of replacing fishmeal without adverse effects [32,33]. Ozherelyeya et al. [34] used compound feed technology, combining naked barley, soy hulls, and sunflower hulls with a minimum amount of fishmeal via extrusion. The findings of this trial showed that the feed developed had adequate levels of crude protein (25–26%) and lysine (1.2–1.5%), supporting growth in sturgeon fingerlings. Moreover, the extrusion process increased digestibility by 25–30% and reduced waste production compared to traditional feed.

Fish-In-Fish-Out (FIFO) is a key metric used to assess the sustainability of aquafeeds. This measures the quantity of wild fish biomass required to produce farmed fish (Figure 5). As per Kok et al. [35], past FIFO values for major farmed species, including sturgeon, were almost 1.0, as the majority of the diet consisted of fish meal and fish oil as the raw material. This indicated that to produce 1 kg of farmed fish, approximately 1 kg of wild fish was required. Interestingly, a recent study by Newton et al. [36] showed that incorporating alternative protein sources, such as plant-based proteins, insect meal, and processed animal protein, reduced the FIFO ratio to less than 0.5, thereby reducing pressure on marine feed sources. The use of alternative protein sources provides several environmental benefits, including reducing overfishing of wild fish, lowering the carbon footprint, reducing waste, and ultimately boosting the farming economy.

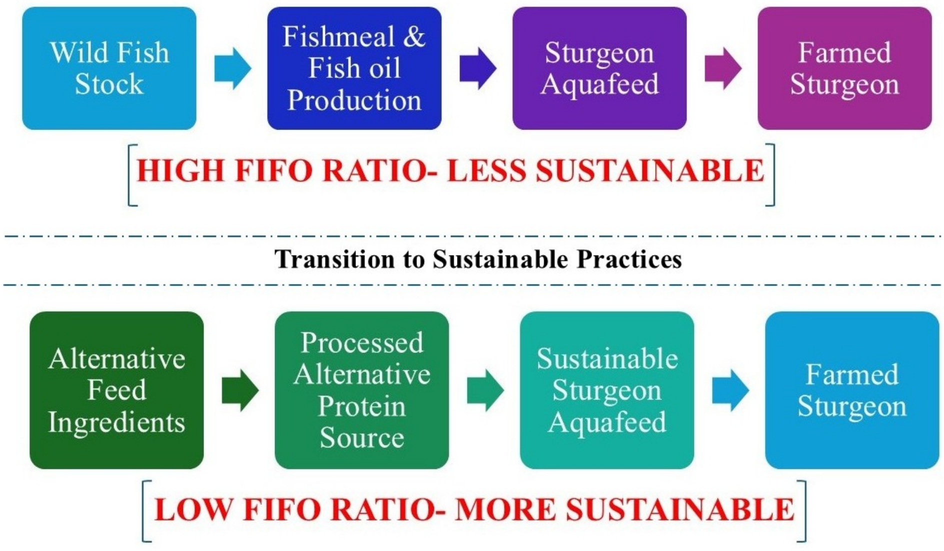

Figure 5. Conceptual diagram illustrating the Fish-In-Fish-Out ratio.

5. Evolution of Commercial Diets: Development and Innovation of Feed Ingredients

As sturgeon aquaculture expanded and the need for sustainable feeding became necessary, formulated feed was first developed in the late 20th century to meet nutritional needs, enhance growth, and improve caviar quality by reducing dependence on wild feed sources [16,37]. Soon after the recognition of specific nutritional needs in sturgeon species, many companies began developing sturgeon-specific diets [4].

Companies like Alltech Coppens, Biomar and Zeigler were some key manufacturers of sturgeon-specific formulated feed during the early 1980s and 1990s. These diets are specifically designed and tailored to mouth size and developmental stage. Alltech Coppens has developed feeds for caviar- and meat-producing sturgeons to enhance growth, improve immune response, and improve nutrient retention [38]. Biomar EFICO sigma, on the other hand, provides specific grower and finisher feeds to meet dietary requirements, with an emphasis on digestibility, nutrient balance, and sustainability [39]. Zeigler provides feed containing high-quality marine proteins and immunostimulants, which enhance survival and health, especially under stressful growth conditions [40].

With the development of commercial feed, innovation and advances in feed ingredients followed. Zhu et al. [41] investigated the metabolic changes in lipids and amino acids during ovarian development in Chinese sturgeon (*Acipenser sinensis*). The findings of this study provided insight into the reproductive physiology of sturgeon and supported nutritional strategies to enhance captive breeding success. Additionally, another study by Zarantoniello et al. [5] examined the physiological effects of a black soldier fly meal-based diet on Siberian sturgeon (*Acipenser baerii*) juveniles. They can be cultivated on a small scale, reducing land use, mitigating climate change, and minimizing water pollution. However, the study highlighted the need to improve the palatability and nutritional balance to ensure feed acceptance and performance in sturgeon. Zhang et al. [42] highlighted that low-protein, high-starch diets can help conserve dietary protein while maintaining growth and metabolic activity, making them a potential strategy for reducing feed costs in sturgeon farming. Li et al. [24] evaluated the use of soybean protein concentrate as a substitute for fish meal in hybrid sturgeon, focusing on methionine supplementation. The key findings showed that the feed conversion ratio and hepatic lipid accumulation increased in the fish. Furthermore, a 0.5% methionine supplementation increased growth and muscle texture compared to diets based on fish meal. Another study conducted by Zhang et al. [43] used rapeseed meal as a substitute for fish meal in hybrid sturgeon. It showed that a 50% substitution of rapeseed could reduce dependence on fishmeal without compromising sturgeon health. These investigations and findings indicate that there are potential sources that can successfully replace fishmeal. Lee et al. [44] compared formulated feed with frozen bloodworms for juvenile lake sturgeon (*Acipenser fulvescens*), and their findings suggest that the formulated diets resulted in better weight gain and a lower feed conversion ratio. However, the advantages and effectiveness varied depending on the species, life stage, feed composition, and fish health.

6. Functional Feeds and Additives: Boosting Sturgeon Health and Performance

Functional feeds are specialized diets that are designed to enhance growth, health, immunity, and reproductive performance in fish. These diets contain bioactive compounds, probiotics, prebiotics, enzymes, and Phyto-additives, which improve feed efficiency and minimize environmental impact [45–47]. In sturgeon farming, functional feed plays a crucial role. Several studies have shown that these diets improve feed digestibility, stress tolerance, and disease resistance [4,37,48].

Bongiorno et al. [49] assessed the use of hydrolyzed microalgae from biorefinery as a potential functional ingredient for Siberian sturgeon (*Acipenser baerii*) aquafeed and found that it could improve growth rates and serve as a sustainable alternative to fishmeal. Similarly, Ghiasi et al. [50] assessed the effect of flaxseed meal supplementation on the growth, blood biochemistry, reproductive hormones and oocyte development in Siberian sturgeon *Acipenser baerii*. The key findings showed that Flaxseed meal can accelerate oogenesis and increase sex steroids in female fish, thus making it a potential feed addictive for broodstock nutrition. A recent study by Barbacariu et al. [51] used wheatgrass juice supplements for sterlet sturgeon (*Acipenser ruthenus*) to enhance the reproductive performance and quality of the larvae. It is suggested that it is a promising functional feed addictive to enhance broodstock health and sustainable farming. A recent study by Liu et al. [48] utilized feed additives, such as lactic acid and betaine byproducts, in juvenile bester sturgeon (*Acipenser hybrid*) feeds, resulting in improved growth, metabolic regulation, and health, as determined by metabolomic profiling.

7. Application of Nutrition: Standardized Feeding Strategies and Regimes

The feeding rate of sturgeon typically depends on water temperature and increasing fish biomass. However, the feeding frequency varies for different life stages of the sturgeon. According to the FAO Sturgeon Hatchery Manual [16], smaller sturgeon have a high metabolic rate and a small gut, requiring lower doses. However, as the fish grows, the feeding frequency decreases [16]. During the early stages, energy is required for skeletal and organ development, necessitating frequent feeding. In contrast, adult fish require energy for health, reproduction, and lipid reserves, often necessitating regular feeding. Hence, it is essential to develop appropriate feeding regimes for each fish stage and feed them accordingly.

Overfeeding fish has several negative consequences, including the accumulation of fat in the liver, which can lead to digestive issues and metabolic stress [52]. Additionally, uneaten food can increase ammonia and nitrate levels, which can be harmful to the fish [53]. This will have a direct impact on the quality of caviar and meat produced for the market. The feeding transition from larvae to fingerlings results in 50–70% mass mortality due to high metabolic demand and an immature digestive system [16], requiring a gradual introduction of artificial diets with live feed. Agh et al. [54] reported that a combination of live feed (Artemia) and formulated diets improved survival and growth in sturgeon larvae. Another study by Lee et al. [55] emphasized that co-feeding live feed with formulated diets during the early larval stages resulted in better growth, survival and hypoxia tolerance in lake sturgeon (*Acipenser fulvescen*s). Such tailored feeding regimes are crucial for maximizing yield and product quality in sturgeon aquaculture. Lujan [56] emphasized that efficient feeding strategies, such as precise feeding, automatic feeders, and real-time monitoring, are vital to minimize waste, enhance feed conversion ratios, and maintain ecological balance. Some studies have explored the use of precise feeding technology, utilizing sensors, algorithms, and real-time monitoring to optimize feeding frequency and quantity. Hu et al. [57] employed a non-contact method to measure sturgeon weight in an intensive aquaculture system, addressing the challenges of manual weighing. This study demonstrated the use of AI-driven weight estimation to improve precision in feeding and management practices, thereby reducing labour intensity and enabling automated feeding. These advancements will help waste management, improve growth, and enhance sustainability.

8. Sustainability Contexts in the Sturgeon Diet

One of the holistic pathways to sustainability involves integrating the One Health framework, which links fish health, human health, and environmental stewardship. This approach helps to ensure biosecurity, lower use of antibiotics, improve food safety and promote sustainable farming that would equally benefit aquatic ecosystems, consumers and producers [58–60]. Bilardello [59] emphasized that the sustainability of sturgeon farming can be achieved through robust biosecurity protocols, vaccination policies, and the use of sustainable feed ingredients to enhance disease resistance and reduce reliance on antibiotics. Such practices will not only improve fish health but also safeguard human health. Recent innovations in circular economy applications have highlighted Enzymatic Hydrolysis (EH) as a sustainable approach for converting fish waste into fish protein hydrolysates (FPH), which are known to be rich in bioactive peptides, amino acids, and functional compounds [61]. Processing of sturgeon by-products for pharmaceutical, nutraceuticals and collagen-based applications is an approach to minimize waste and enhance sustainability [37].

Another revolution involves the use of artificial intelligence. A recent study by Cristea et al. [62] integrated artificial intelligence into a sturgeon recirculating aquaculture system, using convolutional neural networks (CNNs) and the YOLOv3 algorithm to estimate biomass with precision and adjust feed in real time. This approach was found to be useful in reducing waste, improving water quality, and lowering nutrient discharge. A recent project conducted by UC San Diego and its collaborators [63] developed an AI-based imaging system for early sex determination in white sturgeon (Acipenser transmontanus) juveniles, achieving nearly 90% accuracy. Such innovation demonstrates how transitioning sturgeon nutrition from conventional feed practices to more advanced, integrated, data-driven, and sustainable approaches can enhance both fish and human health, manage fish waste, and contribute to achieving sustainability goals. This can possibly place sturgeon farming as a model for a resilient, ethical and sustainable aquaculture development.

9. Conclusions

As aquaculture expands worldwide, it is essential to standardize the nutritional practices in sturgeon farming. This review paper emphasizes the transition phase towards a sustainable approach through alternative feed replacement. This will help enhance productivity, sustainability, and ensure economic viability. The shift from fishmeal and fish oil to alternative protein sources, such as insect meal, plant-based meal, and microalgae, will reduce reliance on wild fish stocks, thereby improving sustainability and lowering the Fish-In-Fish-Out ratio. In addition, the application of functional feeds containing bioactive compounds, probiotics, and antioxidants has further demonstrated the ability to strengthen immune function, improve gut health, and regulate lipid metabolism across various sturgeon species. This has improved feed intake and feed conversion ratios across the different life stages of sturgeon.

Recent studies have investigated the physiology of sturgeon, which could help refine the nutritional strategy for developing juvenile sturgeon and optimize brood fish and caviar yields. These advances are critical, especially for a fish like sturgeon, which has a long gestation period, as they can help achieve early maturity through the nutritional component incorporated into feed. Despite the advances in sturgeon nutrition, further research should focus on species-specific nutritional requirements, digestibility, and nutrient balance to maximize growth, survival, feed conversion ratios, feed efficiency, and product quality for both sturgeon meat and caviar. New studies should involve studying the micronutrients such as vitamins, minerals and essential fatty acids required in different life stages for a more precise formulation of feed. Furthermore, studies should continue to refine and explore alternative protein sources, including plant- and insect-derived sources, to examine the long-term implications for immune function, reproductive performance, and caviar quality. Additionally, research should report the species-specific FIFO ratios to provide a more comprehensive understanding of the ecological implications. Innovations such as integrating Artificial Intelligence for real-time automated feeding, monitoring standard growth conditions, optimizing water quality parameters, and detecting disease can be investigated to ensure sustainable and profitable farming approaches. This will further enhance production efficiency and positively impact the existing marine ecosystem, thereby supporting and achieving long-term success in sturgeon farming through an integrated, AI-driven approach. These gaps could help to develop a resilient, effective and ecologically responsible sturgeon farming system.

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Not applicable.

Conflicts of Interest

The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the author used perplexity and ChatGPT for initial brainstorming and checking the grammatical issues. After using those services, the author developed the contents and edited the layout as needed and takes full responsibility for the content of the published article.

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