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REVIEW

Evaluation of the application and environmental sustainability of alternative feed materials in sturgeon nutrition. A review

Z. Mashood[1], M. Rawski[1,*], B. Kierończyk[2], P. Skrzypczak[1] and J. Mazurkiewicz[1]

[1] Poznań University of Life Sciences, Faculty of Veterinary Medicine and Animal Sciences, Department of Zoology, Laboratory of Inland Fisheries and Aquaculture, Wojska Polskiego 71c, 60-625 Poznań, Poland.
[2] Poznań University of Life Sciences, Faculty of Veterinary Medicine and Animal Sciences, Department of Animal Nutrition, Wołyńska 33, 60-637 Poznań, Poland

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* Corresponding author:
e-mail: mateusz.rawski@up.poznan.pl

ABSTRACT. In this review, sturgeon nutrition was systematically evaluated based on 299 original research articles sourced from reputable journals using commonly employed databases (PubMed and Google Scholar), supplemented by two reviews on the dietary requirements of sturgeon species. This article also details the paucity of nutritional research on sturgeon, updated sturgeon nutritional requirements and feed composition, as well as the environmental sustainability of alternative plant- and animal-based proteins utilised in sturgeon nutrition. Furthermore, the review highlights the lack of data on environmental sustainability assessment parameters for protein alternatives, such as fish in: fish out (FIFO), and estimates sustainability based on feed conversion ratio (FCR), and fishmeal (FM) and fish oil (FO) levels used in diets following standard methodology. Finally, the review provides insights into the potential of using insect protein and fat, especially from *Hermetia illucens* larvae, as a viable and sustainable alternative in the evolving landscape of aquafeed production.

Introduction

Over the past few decades, Acipenseridae species have gained a significant economic, ecological, recreational, and aquacultural value (Hung, 2017). Sturgeons have demonstrated high suitability for aquaculture owing to their rapid growth, stress resistance, favourable production efficiency, advances in nutrient digestibility, and adaptation to farming conditions (Falahatkar, 2018; Zarantoniello et al., 2021). Sturgeons are also known for their superior meat quality and prized caviar, becoming the dominant aquaculture species in China – a key player in the global aquaculture industry (Chebanov and Williot, 2018; Bronzi et al., 2019). Sturgeon production has fluctuated over the years, influenced by factors such as environmental changes and fishing practices (Figure 1). Aquaculture production of these species has been steadily increasing from 2003 until the last published quantification in 2021, primarily driven by the growing market demand for sturgeon products. Increasing consumer income and limited accessibility to wild-sourced sturgeon caviar and meat have been among many other factors driving demand for meat and caviar products from aquaculture (Tavakoli et al., 2021).

Nevertheless, the expansion of sturgeon aquaculture has been motivated by factors beyond economic viability. Dam construction, reduced spawning migration, poaching, overfishing, and environmental pollution have collectively posed serious threats to all sturgeon species (Falahatkar and Nasrollahzadeh, 2011). Consequently, the trade of all Acipenseriformes and their products has been

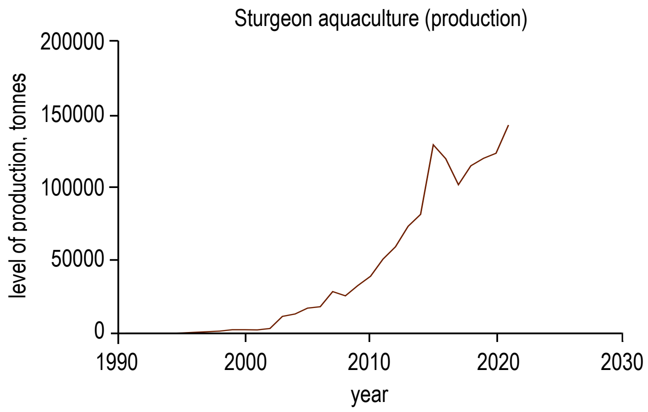

Figure 1. Production level in sturgeon aquaculture (1993–2021) (tonnes) (Bronzi et al., 2019; Elhetawy et al., 2023)

regulated by the Convention on International Trade in Endangered Species (CITES) and EU Wildlife Trade Regulations (Commission Regulation (EU) 338/97), classifying these species as threatened or critically endangered (Chandra and Fopp-Bayat, 2021). This has also led to their classification as critically endangered on the IUCN Red List (Ruban and Mugue, 2022). The survival of this species now depends on restocking initiatives and effective fishery management plans. Sturgeon farming has been intensified to reduce overfishing, especially following the 2006 ban on the export of caviar harvested from wild fish to protect wild stocks (Bestin et al., 2021). Moreover, the aquaculture of endangered species should be considered an active method for environmental and population protection. This approach satisfies market demands without harming natural stocks while increasingly reducing illegal wildlife trade.

The global shift towards using aquaculture as a solution to improve food security and human nutrition is evident. Aquaculture, often considered the aquatic counterpart of agriculture, has experienced rapid growth in recent decades, surpassing wild fisheries in production (Azra et al., 2021). With wild fisheries approaching their biological limits, the increasing global demand for cultured fish has been supported by the expansion of aquaculture. According to an OECD-FAO report, aquaculture production is projected to reach 103 million metric tonnes by 2030, exceeding the production of capture fisheries (FAO, 2020).

However, this unprecedented growth in aquaculture comes with challenges. Nutrition plays a pivotal role in the industry, influencing growth rates, product quality, health, production costs, and environmental sustainability (Prabu et al., 2017). Improving nutritional expertise and developing cost-effective aquaculture diets depend on understanding the nutritional requirements of fish and meeting these needs with balanced diet formulations and appropriate feeding practices (Falahatkar, 2018). Therefore, diet formulation is critical for sustainable fish production due to its direct influence on fish growth performance and health status (Long et al., 2022). Sustainable sourcing of ingredients for fish diets has become a significant concern, particularly with the heavy reliance on wild fish supplies as a major component of farmed fish nutrition (Stankus, 2021). The decreasing availability of fishmeal, a key feed ingredient, has impacted the economic sustainability of aquaculture operations. Additionally, the sourcing of other conventional raw materials, such as soybean meal and cereals, faces challenges, leading to price volatility. Consequently, it is crucial to adopt a comprehensive strategy to achieve aquafeed sustainability. This strategy should focus on using feed components with consistent availability, minimal imports, a relatively small carbon footprint, and most importantly, strict adherence to quality assurance standards. Decisions regarding the use of ingredients recognized as sustainable must consider factors such as the cost of each feed material, the potential for scalable production, the degree of reliance on imports and transport logistics in pursuit of economic sustainability (Boyd et al., 2020). Feed costs account for approximately 50% of the variable costs of aquaculture operations and thus significantly impact economic returns (Pailan and Biswas, 2022). Therefore, the primary objective of meeting the increasing demand for seafood through sustainable aquaculture production is contingent upon the development and utilisation of sustainable aquafeeds, which rely heavily on the composition of ingredients.

Moreover, sustainable aquafeeds will soon be evaluated not only on their nutritional and environmental impacts but also economic and sociocultural elements (Tacon et al., 2022). Therefore, to meet the growing demand for aquaculture products while protecting the delicate balance of aquatic ecosystems, there is an urgent need to investigate and implement sustainable components in aquaculture diets. Alternative protein sources that offer nutritional advantages comparable to those of fishmeal (FM) are extensively researched due to their current scarcity (Daniel, 2018). The increasing demand for food has driven scientists to explore unique and unconventional feed materials such as algae, processed animal protein (PAP), single-cell proteins, and biomass of studies on the two other mentioned species. However, there has been a noticeable upwards trend in studies related to sturgeon physiology and nutrition from 2010 to 2020–2021 (Figure 2a). The majority of research on sturgeon in 2020 (Figure 2b) focused on replacement studies using various insect species to evaluate their effects on sturgeon growth performance, nutrient digestibility, and physiological responses (Jozefiak et al., 2019; Caimi et al., 2020a; Rawski et al., 2020; 2021) Zarantoniello et al., 2021). Interestingly, there is a lack of research publications on the use of *Hermetia illucens* in sturgeon after 2021, a trend is also observed in studies concerning Atlantic salmon and rainbow trout (Figure 2c).

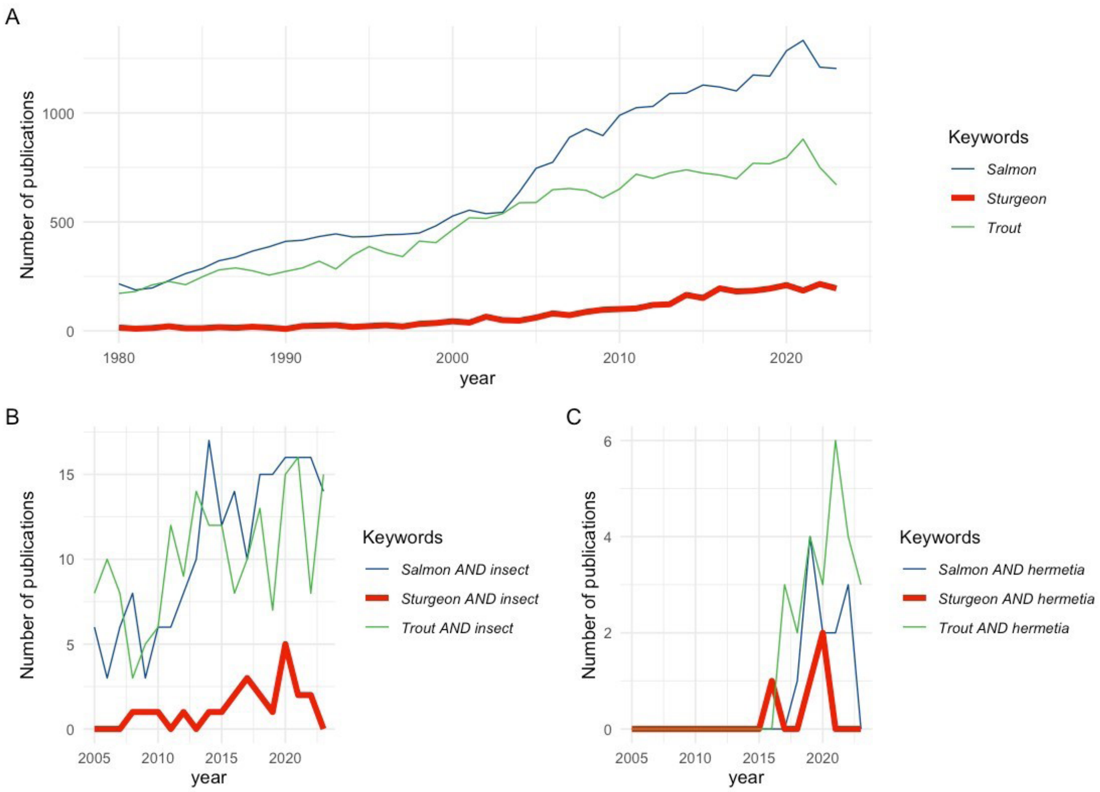

Figure 2. Line graphs showing the trend of publications on (A) sturgeon nutrition, (B) inclusion of insect protein and fat in sturgeon nutrition, (C) inclusion of *Hermetia illucens* protein and fat in sturgeon nutrition

from various insect species (Ameixa et al., 2020). The effort of aquafeed industry to develop a novel generation of sustainable aquafeeds exemplifies its commitment to balancing the growing demand for seafood with the conservation of aquatic ecosystems.

Figure 2 presents the trends in publications on sturgeon nutrition and a comparison with similar studies on Atlantic salmon and rainbow trout. It is worth noting that research on sturgeon nutrition is relatively less extensive compared to the number

Material and methods

Searching strategy and inclusion criteria

This review followed the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Page et al., 2021) and focused exclusively on peer-reviewed studies written in English. The manuscript screening process is shown in Figure 3.

A systematic search was conducted across 299 original research articles sourced from major databases, including PubMed and Google Scholar, and supplemented by two review articles on sturgeon nutrition (Hung, 2017; Falahatkar, 2018). However, one-third of the journals were excluded on the grounds of duplication and the use of identical methodologies related to terrestrial animals. The selection process involved a thorough examination of each journal, and ultimately 58 research publications were excluded for various reasons, including inadequate language translation (26) and insufficient information (32). Additionally, some articles from the 1990s and early 2000s were deemed obsolete. As a result, 144 research studies were initially included into analysis; however, 16 publications were excluded later in the process due to insufficient relevant data regarding the nutritional composition of alternative protein sources and a focus on species that were outside the scope of the present review. In total, 128 research papers were included in this review, with 16 additional studies on the fatty acid composition of dietary oils used in fish nutrition available in the Supplementary Materials.

Since the review articles by Hung and Falahatkar were published in 2017 and 2018, respectively, the present work incorporated 51 new studies. When combined with two prior studies on sturgeon nutrition, the total number of new studies reached 53.

Results and discussion

Nutritional guidelines for sturgeon farming

In sturgeon farming, most farmers typically use generic fish diets, particularly high-energy salmonid diets, containing 40–50% crude protein, 12–20% crude fat, and 18–22 MJ gross energy per kg diet for Siberian sturgeon (*Acipenser baerii*) (Sicuro, 2018), beluga sturgeon (*Huso huso*) (Defaee et al., 2022), green sturgeon (*Acipenser medirostris*) (Zheng et al., 2015), lake sturgeon (*Acipenser fulvescens*) (Lee et al., 2022), white sturgeon (*Acipenser transmontanus*) (Sicuro, 2018), and hybrid sturgeon (Guo et al., 2011; Sicuro, 2018). Until recently, most fish feed companies primarily used commercial salmonid feeds for sturgeon diets, despite the fact that sturgeons have distinct

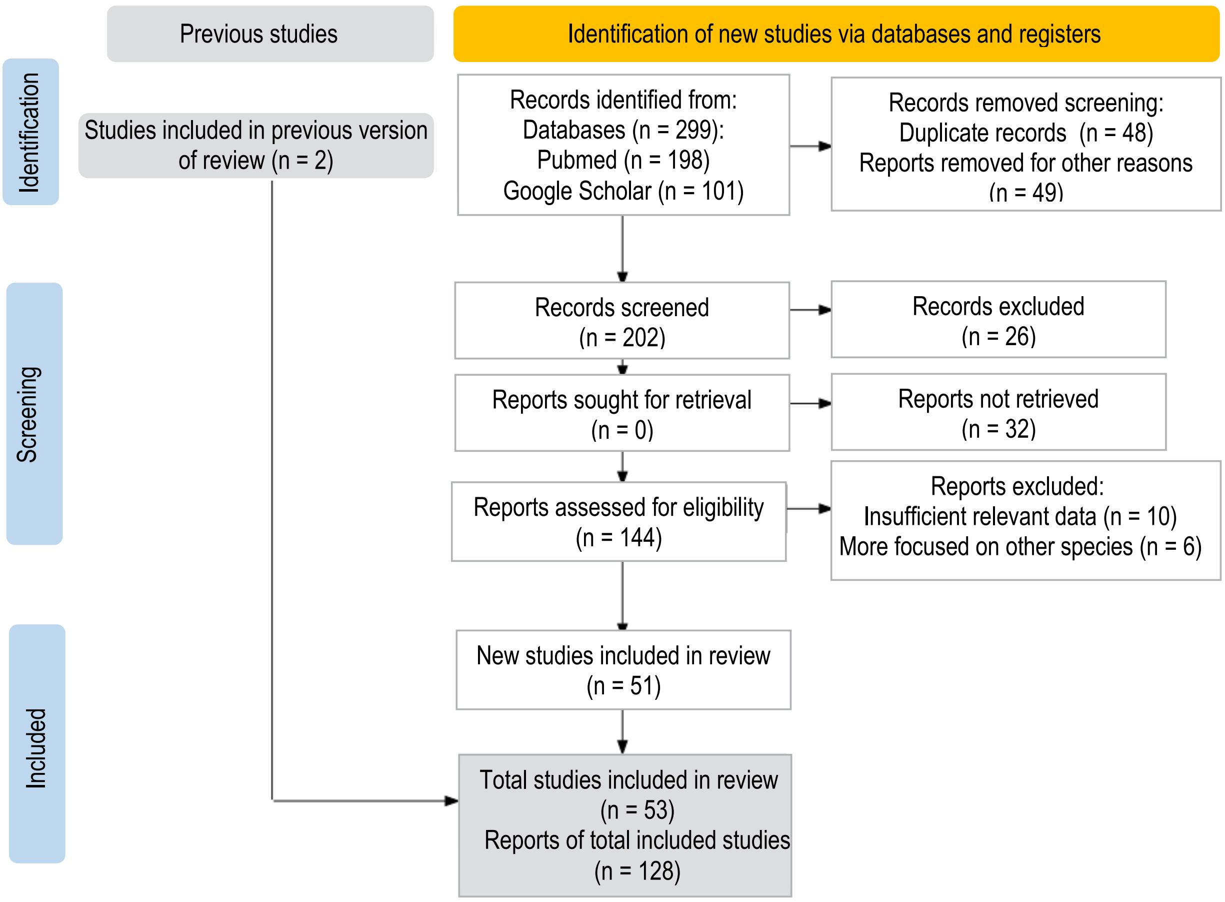

Figure 3. Search strategy and screening process used to qualify manuscripts according to PRISMA guidelines

morphological and physiological characteristics from other fish (Daprà et al., 2009). This was due to the fact that historically, sturgeon farming had not been as widespread as farming of other fish species. However, salmonid diets have produced sufficient results, which did not initially prompt specialised research on sturgeon nutrition.

The dietary crude protein requirements for sturgeons has recently been reduced. Ronyai et al. (2002) reported effective crude protein levels of 29–33%, while Xue et al. (2012) found that Siberian sturgeon diets containing a large proportion of fishmeal substitutes could reach 36% crude protein. Various studies have indicated that the optimal crude protein levels range from 37 to 40.5% for maximum growth of different sturgeon species (Moore et al., 1988; Medale et al., 1995; Xiao et al., 1999; Mohseni et al., 2007; Guo et al., 2011). These levels were reported for the initial body weight (IBW) growth of white sturgeon (145 g IBW), Siberian sturgeon (20 to 40 g IBW), Chinese sturgeon (*Acipenser sinensis*, 8 to 34 g IBW), Persian sturgeon (*Acipenser persicus*, 137 g IBW), and hybrid sturgeon (*A. baerii* × *A. gueldenstaedti*, 25 g IBW), as shown in Table 1. The protein needs among these sturgeon species are relatively consistent, thus it is practical to use a general estimate of 40% crude protein requirement for new species until a precise requirement can be determined through dose-response growth trials (Hung, 2017).

Sturgeons also share traits with other piscivorous species, including rainbow trout (*Oncorhynchus mykiss*), turbot (*Scophthalmus maximus*), cobia (*Rachycentron canadum*), and European sea bass (*Dicentrarchus labrax*). Like these species, they can effectively utilise crystallised amino acids in artificial diets (Zhu et al., 2011). Table 2 outlines the diverse amino acid demand for different sturgeon species, i.e., mainly Siberian sturgeon and white sturgeon (*Acipenser transmontanus*), but also other species of sturgeon. However, knowledge about their requirements for minerals, long-chain polyunsaturated fatty acids (LC-PUFA), phospholipids, cholesterol, and vitamin contents is still limited, as is information on the amino acid needs of other sturgeon species (Kaushik et al., 1991; Xue et al., 2012; Hung, 2017). Falahaktar (2018) also reported that sturgeons have increased requirements for specific amino acids, such as lysine, leucine, or arginine.

Determining the optimal dietary fat requirements for sturgeons depends on factors such as species, life stages, dietary fat sources, diet formulations, and environmental conditions (Hung, 2017; Pelic et al., 2019). This is significant because fish may not maintain their growth rate above the optimal dietary lipid levels, as their excess may cause a reduction in feed intake and lead to metabolic disorders due to excessive lipid accumulation and abnormal oxidative status (Li et al., 2023).

Broken-line analysis has provided information on the dietary lipid requirements of various juvenile sturgeon species: juvenile hybrid sturgeon (*A. baerii* × *A. gueldenstaedtii*; 66.7 g IBW), 111.0 g/kg (Guo et al., 2011); Amur sturgeon (*A. schrenckii*; 4.16 g IBW), 203.1 g/kg (Li et al., 2023); Siberian sturgeon (*A. baerii*; 1419 g IBW), 169.9–176.0 g/kg (Ren et al., 2021); and Beluga sturgeon (*Huso huso*; 50 g IBW), 240 g/kg (Najafi et al., 2017). However, the optimal dietary fat level for species such as *A. baerii* has not been explored throughout their entire life cycle. Although research has been conducted on the effects of various carbohydrate sources in different sturgeon species (Qu et al., 2022; Jiang et al., 2014), little is known about how sturgeons utilise, transport, and excrete D-glucose through their urine. Further research is needed to accurately determine the nutritional requirements, nutrient digestibility, and adequate nutrient balance to achieve optimal growth rates, high feed efficiency, reduced water pollution, and

Table 1. Nutritional needs of sturgeons in size classes

Species	Size, g	Crude dietary protein, g/kg	Crude fat, g/kg	References
Siberian sturgeon (*Acipenser baerii*)	20–40; 14.19*	360–400	169–176	Xue et al., 2012; Ren et al., 2021
Chinese sturgeon (*Acipenser sinensis*)	8–34	400–450	-	Xiao et al., 1999
Beluga sturgeon (*Huso huso*)	1.3–77; 50*	389	240	Mohseni et al., 2013; Najafi et al., 2017
Persian sturgeon (*Acipenser persicus*)	137	400–450	-	Mohseni et al., 2007; Kaushik et al., 1989
Amur sturgeon (*Acipenser schrenckii*)	26	400	203.1	Xu et al., 2012
White sturgeon (*Acipenser transmontanus*)	145	405	258–357	Moore et al., 1988; Hung et al., 1997
Hybrid sturgeon (*Acipenser baerii* x *Acipenser gueldenstaedti*)	25; 66.7	370	111	Guo et al., 2011

* IBW – initial body weight recorded

Table 2. Sturgeon requirements for essential amino acids and selected vitamins (percentage of dietary protein)

Nutrients	Siberian sturgeon (*Acipenser baerii*) [1]	White sturgeon (*Acipenser transmontanus*) [2]	Beluga sturgeon (*Huso huso)*	Amur sturgeon (*Acipenser schrenckii*)
Arginine	2.8	4.8	NR	NR
Lysine	6.3	5.4	NR	NR
Histidine	1.1	2.3	NR	NR
Leucine	3.2	4.3	NR	NR
Isoleucine	2.1	3.0	NR	NR
Phenylalanine	1.5	3.0	NR	NR
Cysteine	NR	0.2	NR	NR
Methionine	NR	2.0	NR	NR
Tryptophan	NR	0.3	NR	NR
Tyrosine	NR	2.3	NR	NR
Valine	2.3	3.3	NR	NR
Threonine	2.2	3.3	NR	NR
Choline, g/kg	1.5 [3]	NR	NR	NR
D_3, IU/kg	683.30–403.27 [4]	NR	NR	NR
A (retinol acetate), IU/kg	NR	NR	NR	1.050 [5]
E, mg/kg	NR	NR	26.6–29.6 [6]	NR
B_1, mg/kg	NR	NR	10–20 [7]	NR

NR – not reported; [1] Kaushik et al. 1991; Falahatkar, 2018; [2] Ng and Hung, 1995; Falahatkar, 2018; [3] Yazdani Sadati et al., 2014; [4] Wang et al., 2017; [5] Wen et al., 2008; [6] Amlashi et al., 2012; [7] Mohseni et al., 2023

the production of high-quality meat and caviar. This knowledge is essential to ensure the success and expansion of intensive sturgeon farming.

FM has traditionally been the primary protein source in carnivorous fish feed due to its high protein content, favourable amino acid profile, palatability, and digestibility (Glencross et al., 2020). However, concerns regarding intensive use, increasing costs, and environmental unsustainability of FM and fish oil (FO) have led to a search for alternative, sustainable protein sources (Dawood, 2022; Hazreen-Nita et al., 2022). Although plant proteins have been considered, challenges such as rising prices, competition with other sectors, antinutritional factors and suboptimal fatty acid and amino acid profiles have impeded their widespread adoption (Gasco et al., 2018; Daniel, 2018). Therefore, insects, which have a long history of application in fish diets, have attracted attention as a sustainable protein source (Nogales-Mérida et al., 2019). Research on insect-based fish nutrition has progressed, identifying promising species for aquafeed production (Kierończyk et al., 2022).

Plant and animal alternative sources in sturgeon nutrition

Sturgeon aquaculture has undergone significant advancements in recent years, particularly in terms of plant-derived protein replacements in diets. However, there is a noticeable gap in research regarding the exploration of alternative animal protein sources in sturgeon nutrition. Tables 3, 4, and 5 in this section provide an overview of the current status of sturgeon nutrition, emphasising the extensive research on plant and animal proteins and highlighting potential areas for future exploration of novel protein sources. In addition, Table 3 also contains an analysis of the chemical composition of selected feed materials used as fishmeal substitutes, which is crucial for formulating diets tailored to the precise nutritional requirements of sturgeons, while reducing reliance on fishmeal.

The inclusion of plant proteins such as maize gluten, pea meal, soybean meal, or hazelnut meal (Table 4) has led to a growing interest in reducing dependence on fishmeal, considering factors such as specific growth rate (SGR) and feed conversion ratio (FCR). Investigations by Sicuro et al. (2012) and Yue et al. (2019) have indicated that the inclusion of maize gluten, pea meal, and soybean meal in the diets of hybrid sturgeon species is feasible and represents a potential path for future research. However, limitations of certain studies, where fish-in : fish-out (FIFO) values are marked as 'not reported', hinder a comprehensive assessment of the sustainability of these alternative diets. Consequently, the FIFO results presented in both tables were estimated based on published data (Jackson, 2009).

The digestibility of plant-based proteins in sturgeon diets is generally lower than that of FM; however, it can be improved through various

Table 3. Chemical composition of selected feed materials used as a replacement for fishmeal in sturgeon studies

Parameters	Raw materials							
	Fish meal	Hazelnut meal	Full-fat BSFL (*Hermetia illucens*)	Mealworm (*Tenebrio molitor*)	Corn gluten	Soybean meal	Poultry byproduct meal	Soy protein concentrate
Crude protein, %	72.28	42.1	35	53.36	66.39	43.77	67.11	64.2
Crude lipid, %	6.68	2.26	29.8	19.28	14.62	1.30	17.12	0.8
Moisture, %	7.64	8.7	NR	NR	10.40	12.30	NR	NR
Crude ash, %	NR	8.2	5.3	7.48	NR	NR	14.53	6.3
Nitrogen-free extract, %	NR	28.64	22.1	7.77	NR	NR	NR	NR
Crude fibre, %	NR	NR	7.9	2.53	NR	NR	NR	NR
Amino acids, % crude protein								
arginine	4.35	4.20	5.47	2.51	4.18	2.96	4.45	4.98
lysine	5.76	0.85	6.82	3.49	4.26	2.57	3.69	4.23
histidine	2.38	1.01	3.25	1.60	1.63	1.13	1.26	1.81
leucine	5.50	1.93	7.83	4.24	5.70	3.34	4.46	5.17
isoleucine	3.26	2.09	4.73	1.46	2.82	1.91	2.46	4.23
phenylalanine	3.05	2.10	7.76	2.38	3.22	2.30	2.48	3.40
cysteine	0.58	3.55	0.76	0.38	0.79	0.67	0.71	NR
methionine	2.14	0.55	2.12	1.28	1.39	0.46	1.27	0.92
glycine	4.30	4.12	6.15	2.52	3.31	1.94	6.24	2.74
tyrosine	2.39	1.77	6.71	2.11	3.03	1.49	NR	2.34
valine	3.83	1.47	6.79	NR	3.38	1.96	3.03	3.40
threonine	3.11	0.76	4.43	2.74	3.17	1.79	2.50	2.73
serine	2.87	3.21	4.88	1.37	3.02	2.33	2.82	3.50
alanine	4.76	3.88	8.21	2.91	3.22	1.84	4.17	NR
proline	2.67	2.67	6.68	2.65	2.73	2.16	4.12	NR
aspartic acid	6.4	5.61	7.30	4.30	13.16	4.98	5.35	7.76
glutamic acid	10.53	8.52	13.1	8.00	9.32	8.21	8.43	12.09

NR – not reported; BSFL – black soldier fly (*Hermetia illucens*) full-fat larvae; based on Zhang et al., 2023, Ariman-Karabulut et al., 2019, Rawski et al., 2020, Józefiak et al., 2019, Gyan et al., 2024, Silva et al., 2023, Chen et al., 2023; Ding et al., 2023

strategies, such as processing techniques, enzyme supplementation, or the use of highly digestible plant protein sources. Despite these improvements, plant-derived feed materials have negative environmental impact and can cause several metabolic disorders in fish due to the presence of antinutritional substances, and amino acid imbalance (Lazzarotto et al., 2015). Furthermore, the use of plant proteins in sturgeon nutrition is limited because Acipenseridae are more sensitive to phytoestrogens than other fish species. This sensitivity can negatively affect sexual maturation, reproduction, and caviar production (Williot et al., 2018). It has been confirmed that Russian sturgeon (*Acipenser gueldenstaedtii*) reared in aquaculture experienced disorders in normal and intersex gonad development when fed diets containing phytoestrogens from plant protein sources like soybean meal (Rzepkowska et al., 2014; Kamaszewski et al., 2017).

When evaluating plant-based protein substitutes, it is also important to consider nutrient retention, particularly of nitrogen and phosphorus. According to the literature, plant-derived diets can help maintain or even improve nutrient retention.

Research on the substitution of FM with animal and insect proteins adds a compelling dimension to the pursuit of sustainable aquafeeds for sturgeons, as shown in Table 5. Notably, a study by Zhu et al. (2011) demonstrated a pioneering approach by incorporating a blend of rendered animal protein from meat, bone meal, poultry by-product meal, and hydrolysed feather meal into the diet of *A. baerii*. Additionally, another mixture of rendered animal proteins has been shown to effectively replace 75% FM in the diet of Siberian sturgeon (Xue et al., 2012). This indicates that a diversified strategy utilising multiple animal protein sources has the potential to enhance both growth performance and feed efficiency in sturgeon farming. The inclusion of alternative insect protein sources, such as black soldier fly (*H. illucens*) and yellow mealworm (*Tenebrio molitor*) meals, as demonstrated by studies of Rawski et al. (2020; 2021) and Józefiak et al. (2019), has yielded promising results. For instance, the use of full fat and defatted *H. illucens* larvae meal in *A. baerii* diets (Rawski et al., 2020; Caimi et al., 2020b) resulted in significant improvements in SGR and FCR, suggesting the

Table 4. Effects of fishmeal replacement with plant-origin proteins on selected production parameters in various sturgeon species

Ingredients	Sturgeon species	Initial weight, g	% ingredient inclusion levels	Fish meal inclusion, g/kg	Level of fishmeal replacement	SGR, % per day	FCR/Feed efficiency	FIFO	References
Corn gluten and pea meal	Hybrid sturgeon (*Acipenser naccarii* × *A. baerii*)	364.8	3.5% of corn gluten	540	-	0.43	1.64	NR	Sicuro et al., 2012
			55% of corn gluten	80	85	0.54	1.30		
Soybean meal (SBM)	*Acipenser persicus*	352.07	0% SBM	550	-	1.09	1.75	NR	Imanpoor and Bagheri, 2012
			50% SBM enriched with phytase	218	60.4	0.85	1.08	NR	
Soy protein concentrate (SPC)	*Acipenser baerii*	24.3	0% SPC	272	-	4.19	1.18	1.34	Mazurkiewicz et al., 2009
			24% SPC	100	63.2	4.01	1.19	0.77	
Soy protein concentrate and rapeseed meal	*Acipenser baerii*	25.0	21% SPC and 7% of rapeseed meal	100	63.2	3.95	1.22	0.79	Mazurkiewicz et al., 2009
Defatted hazelnut meal (HM)	*Acipenser baerii*	283.1	0% HM	600	-	1.1	1.50	3.86	Ariman-Karabulut et al., 2019
			15% HM	450	25	1.0	1.60	3.27	
Plant protein-blend (soybean and wheat gluten meal)	*Acipenser baerii*	39.0	0% PPB	483	-	2.32	1.29	2.36	Yun et al., 2014
			60% PPB	0	100	2.26	1.27	0.21	
Sesame oil cake and corn gluten	*Huso huso*	51	0% sesame oil cake and 0% corn gluten	550	-	2.51	0.6	1.33	Jahanbakhshi et al., 2013
			8% sesame oil cake and 8% corn gluten	453	17.6	2.64	0.6	1.10	
Soy-protein isolate (SPI)	*Acipenser schrenckii*	26.38	0% SPI	400	-	NR	1.69	2.92	Xu et al., 2012
			7.4% SPI	300	25	NR	1.64	2.28	
Cotton protein concentrate (CPC)	*Acipenser baerii*	21.3	0% CPC	500	-	NR	1.09	2.18	Wang et al., 2023
			50% CPC	0	100	NR	1.23	0.34	
Poultry-byproduct meal (PBM)	*Huso huso*	28.42	0% PBM	500	-	3.74	1.21	2.55	Sayed Hassani et al., 2021
			10% PBM	400	20	3.74	1.24	2.16	
Hydrolysed potato starch (HPS)	*Acipenser transmontanus*	25–27	0% HPS	NR	NR	2.33	1.44[FE]	NR	Deng et al., 2005
			45% HPS	NR	NR	2.86	1.50[FE]	NR	

SGR – specific growth rate, FCR – feed conversion ratio, FIFO – fish-in : fish-out, NR – not reported, PPB – plant protein-blend (soybean and wheat gluten meal), HPS – hydrolysed potato starch, [FE] – feed efficiency

potential of insect biomass as a viable alternative to FM. Given that sturgeons naturally consume insects such as chironomids and mayflies in the wild (Guilbard et al., 2007), recent studies have increasingly explored the use of insect meals in aquafeeds. While only a limited number of studies (Katya et al., 2017; Hosseini Shekarabi et al., 2021; Tippayadara et al., 2021) have established optimal levels for insect meals in aquafeed, the current recommendations are primarily based on the results of using insect meal as a primary substitute for FM in diets (Maulu et al., 2022). Insect meal substitution has been explored in various fish species, including rainbow trout (*O. mykiss*), catfish (*Clarias gariepinus*), guppies (*Poecilia reticulata*), Japanese sea bass (*Lateolabrax japonicus*), barramundi (*Lates calcarifer*), Atlantic salmon (*Salmo salar*), Nile tilapia (*Oreochromis niloticus*), and European seabass (*D. labrax*) (Belforti et al., 2015; Khosravi et al., 2018; Wang et al., 2019; Huyben et al., 2019; Józefiak et al., 2019; Fawole et al., 2020; Mikołajczak et al., 2020; Kowalska et al., 2022). In particular, insect meals, such as those derived from *H. illucens* larvae, have been promoted as potential replacements for FM and/or soybean meal in fish nutrition, showing promising results in various species. However, it is essential to consider certain challenges associated with insect meal substitution, as highlighted by Randazzo et al. (2021). Insects may inherently contain lower

Table 5. Effects of fishmeal replacement with animal-origin and insect proteins on selected production parameters in various sturgeon species

Ingredients	Sturgeon species	Initial weight, g	% ingredient inclusion levels	Fish meal inclusion, g/kg	Level of fishmeal replacement	SGR, % per day	FCR	FIFO	References
Rendered animal protein – BAP (40% meat and bone meal, 40% poultry byproduct meal, and 20% hydrolysed feather meal)	*Acipenser baerii*	28.9	0% BAP	480	-	NR	1.08	2.01	Zhu et al., 2011
			25% BAP enriched with crystallized amino acids	240	50	NR	1.08	1.06	
Full-fat black soldier fly larvae meal (BSFL) (*Hermetia illucens*)	*Acipenser baerii*	14.4	0% BSFL	261	-	1.91	0.88	1.04[R]	Rawski et al., 2020; Rawski et al., 2021
			30% BSFL	101	61.3	2.20	0.68	0.26[R]	
Full-fat black soldier fly larvae meal (BSFL) (*Hermetia illucens*)	*Acipenser baerii*	640	0% BSFL	260	-	1.03	1.47	1.39	Jozefiak et al., 2019
			15% BSFL	184	29.2	1.03	1.48	0.99	
Mealworm (*Tenebrio molitor*) meal	*Acipenser baerii*	640	0% TM	260	-	1.03	1.47	1.39	Jozefiak et al., 2019
			15% TM	156	40	1.03	1.47	0.83	
Black soldier fly (*Hermetia illucens*) larvae meal	*Acipenser baerii*	24.2	0% BSFL	700	-	1.59	1.03	2.85	Caimi et al., 2020b
			18.5% BSFL	525	25	1.51	1.08	2.33	

SGR – specific growth rate, FCR – feed conversion ratio, FIFO – fish-in : fish-out, NR – not reported, BAP – blend of rendered animal protein, TM – mealworm (*Tenebrio molitor*) meal, BSFL – black soldier fly (*Hermetia illucens*) larvae meal

levels of n-3 PUFAs compared to other animals. If insect rearing practices do not include appropriate enrichment, the resulting aquafeeds may also exhibit reduced n-3 PUFA levels. For instance, Zarantoniello et al. (2021) found that replacing 50% FM with *H. illucens* larvae meal significantly lowered the levels of n-3 fatty acids. This reduction led to compromised growth and reduced SGR in Siberian sturgeon, which could potentially be attributed to the use of energy for the conversion of linoleic acid and α-linolenic acid to eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) rather than solely for growth. Nevertheless, a study by Caimi et al. (2020b) indicated that the growth performance, condition factor, and whole-body composition of Siberian sturgeon could be effectively maintained by replacing up to 25% FM with highly defatted *H. illucens* larvae meal. The study also suggested the possibility of substituting up to 18.5% FM with *H. illucens* larvae meal without compromising fish welfare. Additionally, Józefiak et al. (2019) reported that replacing 30% and 40% FM in Siberian sturgeon diets with 18.4% *H. illucens* and 15.6% *T. molitor* full-fat meals, respectively, resulted in growth performance and feed efficiency comparable to those of the control diet. Additionally, this study found that diets containing insect meal with *H. illucens* positively influenced the gut microbiome composition and intestinal morphology of juvenile Siberian sturgeon. It should be noted that the inclusion of insect meals in sturgeon diets requires careful management to avoid potential adverse effects. Caimi et al. (2020b) reported that the inclusion of highly defatted *H. illucens* meal at certain levels reduced feed intake and apparent digestibility coefficient (ADC) of crude protein in Siberian sturgeon juveniles. Specifically, an inclusion level of 185 to 375 g/kg (25 to 50% FM replacement) resulted in reduced feed intake and ADC, while supplementation of 750 g/kg (100% FM replacement) led to complete feed avoidance by the fish. These findings emphasise the importance of determining the optimal inclusion levels of insect meals in sturgeon diets to balance nutritional benefits without compromising palatability.

Diversity of insect-derived materials

Eight insect species, i.e., silkworm (*Bombyx mori*), black soldier fly (*H. illucens*), housefly (*Musca domestica*), mealworm (*T. molitor*), lesser mealworm (*Alphitobius diaperinus*), house cricket (*Acheta domesticus*), banded cricket (*Gryllodes sigillatus)*, and Jamaican field cricket (*Gryllus assimilis*) have demonstrated significant potential for use in industrial aquafeed production (Henry et al., 2015; Nogales-Mérida et al., 2019). Among these, *H. illucens* is particularly favoured for its beneficial fatty acid profile (rich in lauric acid), and chitin content, which are known to stimulate immune system function (Askarian et al., 2012; Palma et al., 2019; Belghit et al., 2019; Mikołajczak et al., 2023). Additionally, regulatory advancements, such as the approval of insect-derived PAP in Europe since July 2017, reflect a growing acceptance of insects as a viable component in aquafeeds (Commission Regulation (EU) 2017/893). Increasing investments in start-ups focusing on large-scale insect meal production further support this trend (Rumbos et al., 2021). Insect meals contain bioactive compounds such as chitin, fatty acids, and antimicrobial peptides

(AMPs), which contribute to their prebiotic, antioxidant, and antimicrobial properties, enhancing animal health and counteracting antimicrobial resistance (Gasco et al., 2018; Veldkamp et al., 2022).

However, despite these advantages, the nutritional value of insect meals can vary significantly depending on factors such as species, rearing techniques, and manufacturing methods. This variability complicates the nutritional optimisation of insect-based feeds for animals. Differences in defatting processes and substrate chemical composition can impact protein and PUFA contents (Zarantoniello et al., 2021; Alfiko et al., 2022). Nevertheless, insect farming is recognised for its sustainability, with minimal environmental impact compared to traditional high-protein sources, offering advantages in terms of land use, water consumption, and greenhouse gas emissions (Gasco et al., 2020; Pulido-Rodriguez et al., 2021). However, the incorporation of insect meals into fish diets faces challenges due to the high chitin content. This compound, prevalent in insect exoskeletons, is poorly digested by fish due to the low activity of enzymes related to chitin breakdown (Gasco et al., 2016). However, at low concentrations, chitin exhibits immunostimulatory, bacteriostatic, antifungal, and antimicrobial properties (Henry et al., 2015; 2018). Moreover, AMPs such as defensins and cecropins present in insects are effective against both Gram-positive and Gram-negative bacteria, offering potential applications as organic antibiotics or antifungal agents (Żyłowska et al., 2011; Yi et al., 2014). Considering these characteristics, the type of insect larvae, their form (fresh, dry, whole, ground, or defatted), and the processing method that affects nutrient composition (sun drying, thermal treatment, lipid extraction) are pivotal factors influencing nutrient utilisation outcomes in aquaculture species (Gasco et al., 2018). Despite the challenges associated with high chitin content, strategies such as the use of chitinolytic bacteria and careful consideration of insect-rearing conditions offer potential solutions (Hameed et al., 2022). Experiments replacing FM with insect meals have shown promising results, but caution is advised when exceeding a 30% substitution threshold, as it may inhibit fish growth (Hua, 2021; Liland et al., 2021). Nonetheless, ongoing research and strategic interventions position insect meal as a viable and sustainable alternative in the evolving landscape of aquafeed production.

Redirection of dietary fat towards insect fat in sturgeon nutrition

Although FO is generally considered the benchmark for dietary fat in aquaculture, it is increasingly apparent that alternative lipid sources can effectively replace FO in several species (Trushenski and Rombenso, 2020; Mata-Sotres et al., 2021). To promote the sustainability of feed ingredients, fish oil has been replaced by a wide range of alternative dietary fat sources, including animal-derived fats (e.g., pig lard, poultry fat), insect fats, and oils of plant origin (e.g., coconut oil, and rapeseed oil) (Gou et al., 2023; Xu et al., 2021; Zhou et al., 2016; Sankian et al., 2019; Fawole et al., 2020). While recent research has investigated the use of dietary insect fat in other fish species, e.g., rainbow trout (*O. mykiss*) and juvenile *Onychostoma macrolepis* (Gou et al., 2023), its potential for enhancing nutrient bioavailability in sturgeon nutrition remains unexplored.

Because of the carnivorous nature of sturgeons and significant quantities of beneficial lauric acid and saturated fatty acids found in *H. illucens* fat, its use can be effective in feed utilisation in sturgeon nutrition. Although a significant drawback of using insect oil as a potential alternative source is its relatively low LC-PUFA content, its moderate levels of monounsaturated fatty acids (MUFAs) and high content of saturated fatty acids (SFAs) can be used to optimise production performance and ensure high retention of DHA and EPA. This is accomplished through a physiological process known as the LC-PUFA 'sparing effect', which has proven effective in many cases (Rombenso et al., 2015; 2018; Marques et al., 2021). Interestingly, the degree of tissue fatty acid modification is influenced by the fatty acid profile of alternative lipid sources (Mata-Sotres et al., 2021). Table 6 lists the fatty acid profile of common alternative oils employed in fish nutrition and compares them with the fatty acid profile of fat from *H. illucens*.

It was reported that feeding juvenile white sturgeon high-fat diets led to enlarged ovarian adipocytes compared to low-fat diets, potentially affecting reproductive ability and caviar yield (Treanor et al., 2018). Conversely, the growth of Russian sturgeon was demonstrated to improve in response to high-lipid diets, demonstrating the ability of these species to utilise high dietary lipid levels (up to 250 g/kg) (Zhu et al., 2017). Body weight gain of Beluga sturgeon (*H. huso*) was shown to considerably increase with incrementing dietary lipid levels from 150 g/kg to 300 g/kg, without significant changes in FCR or feed intake (Keramat-Amirkolaie

Table 6. Fatty acid profile of black soldier fly (*Hermetia illucens*) larvae oil (fat) (BSFLO) and other common fat sources used in fish nutrition, % [1]

Fatty acid	Dietary fat									
	FO	BSFLO	SO	LO	RO	PO	PL	CO	CNO	CAM
C12:0	0.09 ± 0.13	38.08 ± 1.89	NR	0.02 ± 0.00	NR	NR	NR	0.06 ± 0.00	53.98 ± 0.00	0.01 ± 0.00
C14:0	6.37 ± 2.78	7.54 ± 2.11	0.09 ± 0.01	0.17 ± 0.17	0.06 ± 0.00	1.08 ± 0.00	1.79 ± 0.45	0.07 ± 0.00	20.97 ± 0.00	0.05 ± 0.01
C16:0	20.83 ± 5.77	14.97 ± 1.94	11.12 ± 0.57	5.25 ± 0.31	4.54 ± 0.36	29.90 ± 0.00	25.25 ± 3.74	11.80 ± 0.00	10.86 ± 0.00	5.78 ± 0.23
C18:0	4.05 ± 0.93	2.35 ± 1.59	3.86 ± 0.41	3.93 ± 0.75	2.00 ± 0.17	3.07 ± 0.00	15.20 ± 4.24	2.26 ± 0.00	3.60 ± 0.00	2.39 ± 0.00
∑SFA	29.91 ± 5.40	66.83 ± 0.08	15.0 ± 1.01	9.52 ± 0.66	7.73 ± 0.54	41.95 ± 9.69	47.99 ± 0.00	13.93 ± 1.73	90.76 ± 0.00	10.35 ± 0.88
C16:1n-7	7.56 ± 4.41	2.12 ± 0.42	0.09 ± 0.01	0.12 ± 0.07	0.21 ± 0.02	0.25 ± 0.00	1.78 ± 0.46	0.12 ± 0.00	0.06 ± 0.00	0.11 ± 0.04
C18:1n-9	13.55 ± 3.94	15.29 ± 2.71	23.30 ± 4.93	17.77 ± 2.25	59.00 ± 3.41	49.64 ± 0.00	38.96 ± 6.14	22.84 ± 0.00	5.82 ± 0.00	14.42 ± 2.52
C20:1n-9	3.9 ± 1.06	0.44 ± 0.52	0.56 ± 0.00	0.16 ± 0.00	1.70 ± 0.05	0.27 ± 0.00	0.66 ± 0.00	0.44 ± 0.00	NR	9.98 ± 1.31
C22:1n-9	1.66 ± 2.27	0.05 ± 0.00	NR	NR	0.81 ± 0.60	NR	NR	NR	NR	1.38 ± 0.00
C24:1n-9	0.57 ± 0.11	0.20 ± 0.00	NR	NR	0.14 ± 0.05	NR	NR	NR	NR	NR
∑MUFA	26.60 ± 10.05	18.21 ± 3.82	25.28 ± 1.76	18.75 ± 2.05	60.30 ± 2.95	43.59 ± 9.31	40.37 ± 5.14	28.27 ± 5.75	7.25 ± 0.00	33.10 ± 2.12
C18:2n-6	4.44 ± 2.05	12.3 ± 2.95	51.44 ± 2.72	14.47 ± 1.54	21.71 ± 3.15	11.75 ± 3.75	11.81 ± 1.99	54.75 ± 4.40	1.76 ± 0.00	20.41 ± 4.32
C20:4n-6	0.89 ± 0.17	0.07 ± 0.00	NR	NR	NR	NR	NR	0.03 ± 0.00	0.03 ± 0.00	0.00 ± 0.00
n-6∑PUFA	6.86 ± 2.30	0.08 ± 0.00	52.14 ± 2.09	13.95 ± 1.77	23.07 ± 3.91	11.79 ± 3.80	12.71 ± 3.55	58.00 ± 0.00	NR	25.9 ± 0.00
C18:3n-3	1.85 ± 0.77	0.73 ± 0.31	5.54 ± 0.59	53.17 ± 3.91	9,21 ± 1.19	0.21 ± 0.01	0.60 ± 0.46	0.8 ± 0.14	0.04 ± 0.00	37.16 ± 0.21
C20:3n-3	0.45 ± 0.51	0.25 ± 0.10	NR	0.07 ± 0.00	0.05 ± 0.00	NR	NR	NR	NR	0.03 ± 0.00
C20:5n-3	12.59 ± 5.05	0.98 ± 0.00	NR	NR	NR	NR	NR	NR	NR	0.00 ± 0.00
C22:6n-3	12.01 ± 4.04	NR	NR	NR	NR	NR	NR	NR	NR	0.00 ± 0.00
n-3∑PUFA	28.61 ± 6.84	NR	6.08 ± 0.79	55.79 ± 3.51	8.84 ± 1.41	0.21 ± 0.01	0.86 ± 0.21	0.70 ± 0.00	NR	34.41 ± 4.68
n-3/n-6	4.71 ± 1.59	NR	0.10 ± 0.01	3.98 ± 0.311	0.39 ± 0.13	0.01 ± 0.01	0.08 ± 0.04	0.00 ± 0.00	NR	1.45 ± 0.35

C12:0 – lauric acid, C14:0 – myristic acid, C16:0 - palmitic acid, C18:0 – stearic acid, C16:1n-7 – palmitoleic acid, C18:1n-9 – oleic acid, C20:1n-9 – 11-eicosenoic acid or gondoic acid, C22:1n-9 – erucic acid, C24:1n-9 – nervonic acid, C18:2n-6 – linoleic acid, C20:4n-6 – arachidonic acid, C18:3n-3 – α-linolenic acid, C20:3n-3 – eicosatrienoic acid, C20:5n-3 – eicosapentaenoic acid, C22:6n-3 –docosahexaenoic acid
NR – not reported; SFA – saturated fatty acid; MUFA – monounsaturated fatty acid; PUFA – polyunsaturated fatty acid; FO – fish oil; SO – soybean oil; LO – linseed oil; RO – rapeseed oil; PO – palm oil; PL – pork lad; CO – corn oil; CNO – coconut oil; CAM – camelina oil. [1] the presented values are based on the literature listed separately in the supplementary material.

et al., 2012). Similarly, white sturgeon effectively utilised dietary lipids at concentrations between 258 and 357 g/kg (Hung et al., 1997). In contrast, optimal dietary lipid levels for hybrid sturgeons (*A. baerii* × *A. gueldenstaedtii*) were reported to be 111 g/kg, indicating species-specific variation in lipid utilisation (Table 1). Sturgeon larvae reportedly exhibit high energy demands and relatively high lipase activity and lipid absorption capacity during development (Sicuro et al., 2015). Moreover, sturgeon juveniles show a high ability to assimilate, digest, and utilise high-lipid diets (Pang et al., 2022; Mohseni et al., 2023).

Studies have also examined the physiological responses of Siberian sturgeon juveniles fed a full-fat insect-based diet, including *H. illucens* meal, in aquaponic systems. The addition of enriched *H. illucens* meal to sturgeon diets has been shown to affect growth performance, fillet fatty acid composition, liver and gut integrity, gene expression related to growth, stress, and immune response, as well as the gut microbiome (Rawski et al, 2021; Zarantoniello et al., 2021). Considering the potential of replacing FO with insect fat, further research on sturgeon nutrition should be conducted. These future studies should focus on inclusion levels and enrichment procedures to ensure optimal growth and health outcomes, as well as the underlying mechanisms influencing growth performance and nutritional efficiency of sturgeons fed insect-based diets.

Conclusions

This review underscores the ongoing transition in sturgeon aquaculture towards sustainable feed alternatives, showing promising results from plant- and animal-based protein replacements. Future studies should not further explore nutritional aspects, but also systematically report fish-in : fish-out (FIFO) values to provide a more comprehensive understanding of ecological implications. Additionally, exploring potential synergies between plant and animal protein sources may present novel opportunities for optimising sturgeon aquafeeds, promoting both economic viability and environmental sustainability in this key sector. This review also provided insight into the innovative use of insect-based alternatives as lipid and protein sources in sturgeon nutrition.

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Conflict of interest

The Authors declare that there are no conflicts of interest.

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