

CASPIAN SAND SMELT (*ATHERINA BOYERI CASPIA*) MEAL AS A SUSTAINABLE ALTERNATIVE TO KRILL MEAL IN DIETS FOR JUVENILE RUSSIAN STURGEON (*ACIPENSER GUELLENSTAEDTII*) REARED IN RAS

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ABSTRACT

This study presents a comparative statistical analysis of growth performance in juvenile Russian sturgeon (*Acipenser gueldenstaedtii*) reared under different dietary treatments in a recirculating aquaculture system (RAS). Experimental feeds included a control diet with 100% krill meal and an experimental diet in which 25% of the krill meal was replaced with big-scale sand smelt meal. The 120-day experiment evaluated final body weight, specific growth rate (SGR), feed conversion ratio (FCR), survival rate, and biochemical composition. We used two-way ANOVA (diet $\times$ time) and Tukey’s post hoc test to assess treatment effects. Results showed significant improvements in final weight (160.4 ± 25.9 g vs 154.6 ± 25.3 g, $p = 0.032$), survival rate ($87.8 \pm 1.8\%$ vs $84.4 \pm 2.1\%$, $p = 0.041$), and FCR (1.31 ± 0.08 vs 1.39 ± 0.07 , $p = 0.028$) in the experimental group. Biochemical parameters did not differ significantly. The findings show that partially replacing krill meal with large-scale sand smelt meal improves growth performance and feed efficiency without compromising fish health, supporting the use of local raw materials in sturgeon aquaculture.

Keywords: Russian sturgeon, RAS, Compound feed, Large-scale sand smelt, Growth performance, Feed conversion ratio, ANOVA.

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1. INTRODUCTION

Global aquaculture continues to expand rapidly and currently provides more than 58% of all aquatic animals consumed worldwide. The sustainable development of this sector largely depends on the availability of nutritionally balanced and economically efficient feeds, as feed costs typically account for 50–70% of total production expenses in intensive aquaculture systems (FAO, 2024). Consequently, the search for alternative protein ingredients that can partially replace expensive imported feed components has become a major priority in modern aquaculture (Waller, 2024).

Russian sturgeon *A. gueldenstaedtii* is one of the most valuable aquaculture species because of its rapid growth, high-quality meat, and caviar production. As restrictions on commercial harvest of wild sturgeon populations increase, intensive aquaculture using recirculating aquaculture systems (RAS) has become increasingly important for maintaining market supply while reducing fishing pressure on natural stocks (Dudu & Georgescu, 2024). However, the economic sustainability of sturgeon farming depends heavily on feed formulation, particularly because marine-derived protein ingredients are costly (Fajardo et al., 2025; Zhumatova et al., 2026).

Fish meal and krill meal remain the principal protein sources in commercial sturgeon feeds because of their excellent amino acid balance, high digestibility, and favorable effects on fish growth. Nevertheless, increasing prices, fluctuations in global supply, and growing concerns regarding the sustainable exploitation of marine resources have stimulated extensive research on alternative protein sources. Numerous studies have demonstrated that partial replacement of conventional marine ingredients with locally available raw materials may reduce production costs by 10–20% without negatively affecting fish growth, feed utilization, or physiological condition in carnivorous fish species (Hardy, 2010; Salter & Lopez-Viso, 2021; Naylor et al., 2021; Alieva et al., 2023).

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The Caspian region possesses substantial biological resources that remain underutilized in aquafeed production. One such resource is the large-scale sand smelt, *Atherina boyeri caspia*, a low-value commercial fish often caught as bycatch in sprat fisheries (Patimar et al., 2009; Abdybekova et al., 2021). Previous investigations have shown that this species is characterized by crude protein content of 16-18% and relatively low lipid concentration <5%, making it a promising raw material for fish meal production. In addition to its nutritional value, utilizing large-scale sand smelt may support the development of regional feed industries and reduce dependence on imported ingredients, in accordance with circular bioeconomy principles (Troell et al., 2014; Hayes, 2018; Ponomarev et al., 2026).

Despite increasing interest in alternative protein sources for aquaculture, information regarding the use of large-scale sand smelt meal in diets for Russian sturgeon remains extremely limited. Most published studies have focused on plant proteins, insect meals, or other marine ingredients, whereas the biological effectiveness of sand smelt meal has received little scientific attention. Consequently, experimental evidence on its effects on growth performance, feed conversion efficiency, survival, and body composition in juvenile sturgeon reared under intensive RAS conditions remains insufficient (Hardy, 2010; Coroian & Dăescu, 2026).

We hypothesized that partially replacing krill meal with fish meal produced from big-scale sand smelt would maintain or improve growth performance and feed utilization without adversely affecting the physiological condition of juvenile Russian sturgeon (Moloudinia et al., 2019). Therefore, this study aimed to evaluate the effects of replacing 25% of krill meal with big-scale sand smelt meal in compound feeds on growth performance, feed conversion ratio, survival, condition factor, and the biochemical composition of juvenile Russian sturgeon cultured in a recirculating aquaculture system.

Thus, a literature review shows that partial replacement of fish meal is promising; however, it requires a detailed study of the effectiveness of using large-scale sand smelt in compound feed in commercial sturgeon farming. The relevance of the research topic is beyond doubt, as it addresses the need for an alternative source of fish meal using local raw materials.

Recent advances in aquaculture nutrition indicate that replacing conventional marine protein ingredients should be considered not only in terms of protein content, but also in relation to amino acid balance, digestibility, palatability, feed conversion, fish health, and the economic characteristics of the final diet. Recent systematic reviews have demonstrated that alternative proteins can successfully replace a proportion of fish meal in aquafeeds, although the optimal inclusion level varies considerably according to fish species, ingredient type, processing method, and dietary formulation (Mugwanya et al., 2023; Qian et al., 2024; Serra et al., 2024). In particular, carnivorous fish generally respond more sensitively to high replacement levels because plant and some alternative animal proteins may have imbalanced essential amino acids, reduced digestibility, or anti-nutritional compounds (Hossain et al., 2024). Consequently, moderate partial replacement is increasingly considered a practical strategy because it retains the nutritional advantages of fish-derived ingredients while reducing the amount of conventional marine protein required. Recent experimental studies have reported successful partial replacement of fish meal with plant proteins, microbial biomass, insects, marine by-products, and other unconventional ingredients without substantial reductions in growth or feed utilization (Gunathilaka et al., 2023; Santillan et al., 2024; Li & Cho, 2024; Asimaki et al., 2025).

Evidence from sturgeon aquaculture is particularly relevant because sturgeons have relatively high dietary protein requirements and are commonly fed diets containing substantial proportions of high-quality marine ingredients. Recent studies have shown that sturgeon responses to alternative protein sources depend strongly on the replacement level. Wnęk-Auguścik et al. (2024) reported that rapeseed meal could replace 10–30% of fish meal in diets for Siberian sturgeon without negative effects on growth, muscle composition, or physiological condition. Similarly, Zhang et al. (2025) found that replacing less than 50% of fish meal with rapeseed meal in hybrid sturgeon diets had limited effects on growth performance and fish health, whereas higher replacement levels progressively reduced final body weight, weight gain, and survival. In contrast, complete replacement of fish meal with cottonseed protein concentrates in *A. schrenckii* significantly reduced weight gain and feed efficiency and altered whole-body amino acid composition and digestive physiology (Wang et al., 2023). These contrasting findings show that the success of alternative protein ingredients depends strongly on the degree of substitution and the ingredient's nutritional characteristics. Therefore, evaluating a moderate 25% replacement level, as applied in the present study, is scientifically justified and may provide a suitable balance between reducing conventional marine ingredients and maintaining the diet's nutritional quality.

Recent research has also demonstrated the potential of aquatic and animal-derived resources as alternatives to conventional fish meal. Partial replacement of fish meal with shrimp waste meal in juvenile beluga sturgeon maintained growth and nutritional characteristics at moderate inclusion levels and enhanced several innate immune parameters, demonstrating the potential of aquatic processing by-products in sturgeon feeds (Taheri et al., 2025). Similarly, marine proteins recovered from processing side-streams have maintained growth and welfare performance comparable to conventional fish meal in Atlantic salmon, supporting the recovery of valuable proteins from underutilized aquatic biomass (Sixten et al., 2025). Other studies have reported positive responses to marine or aquatic alternative ingredients, including polychaete meal, microalgae, and fishery by-products, indicating that locally

available aquatic biomass can represent a nutritionally valuable component of sustainable aquafeeds (Trevi et al., 2023). Importantly, recent studies have also shown that alternative ingredients do not necessarily need to completely replace fish meal to provide nutritional and economic benefits. Moderate inclusion levels may maintain growth and feed efficiency while reducing dependence on conventional marine resources (Li & Cho, 2024). This supports the rationale for investigating large-scale sand smelt meal as a partial rather than complete substitute for krill meal in Russian sturgeon diets.

Another important consideration is the nutritional quality of the replacement ingredient. The amino acid profile of an alternative protein source must match the requirements of the target fish species, while digestibility and palatability determine how effectively dietary nutrients are converted into biomass. Recent studies have demonstrated that nutritional deficiencies can become apparent when alternative proteins are included at excessive levels. For example, soybean protein concentrate impaired growth and protein utilization in hybrid sturgeon when methionine was not adequately supplemented, whereas methionine supplementation restored growth performance and improved intestinal and hepatic responses (Li et al., 2025). Similar dose-dependent effects have been reported for rapeseed meal and other plant-derived ingredients in carnivorous fish (Qian et al., 2024; Zhang et al., 2025). Conversely, recent research using *Chlorella vulgaris* in Siberian sturgeon demonstrated that an appropriately formulated alternative-protein diet could improve growth, digestive enzyme activity, antioxidant capacity, and immune responses (Bayati et al., 2025). These findings emphasize that the nutritional evaluation of alternative ingredients should consider the complete biological response of fish rather than crude protein concentration alone. In the present study, fish meal produced from large-scale sand smelt may be advantageous because it is an animal-derived aquatic protein source and may provide a nutrient profile more compatible with the carnivorous feeding requirements of Russian sturgeon than many plant-derived alternatives.

Using locally available aquatic resources also aligns with the current transition toward circular and resource-efficient aquaculture. Recent studies emphasize that sustainable aquafeed development should reduce dependence on finite marine resources while increasing the use of processing by-products, regional biomass and other materials that would otherwise have limited economic value (Chary et al., 2024; Ma & Hu, 2024; Mahmud et al., 2025). Integrating fishery by-products and other locally available resources into aquafeeds can support circular nutrient flows and potentially reduce the environmental burden associated with producing and transporting conventional feed ingredients (Serra et al., 2024; Hossain et al., 2024). Similar approaches have been proposed for microbial proteins, insect meals, algae, and aquatic processing residues, all of which have been investigated as components of next-generation aquafeeds (Santillan et al., 2024; Siddik et al., 2024; Asimaki et al., 2025). In this context, using *Atherina boyeri caspia* from the Caspian region represents a potentially important regional strategy because it combines feed innovation with more efficient use of available aquatic biomass. Nevertheless, the nutritional composition, digestibility, amino acid and fatty acid profiles, processing characteristics, and economic value of large-scale sand smelt meal require further investigation before recommending wider commercial application. The present study therefore provides an initial experimental basis for assessing this locally derived marine protein source in Russian sturgeon aquaculture and contributes to the broader development of sustainable feed strategies for intensive RAS production.

The purpose of the study is to compare traditional and experimental compound feeds with the inclusion of fish meal from Caspian sand smelt in the cultivation of juvenile Russian sturgeon in RAS.

2. MATERIALS AND METHODS

2.1. Experimental Design and Rearing Conditions

The 120-day experiment was conducted at Caspian Royal Fish LLP from July to October 2025. Juvenile Russian sturgeon with an initial weight of 30 ± 2 g were distributed into control and experimental groups (300 fish per group) and maintained in replicated tanks with a 4 m² area. Stocking density was 25 kg/m². Fish were reared in a RAS with water temperature 20–22°C, dissolved oxygen 7–8 mg/L and pH 7.2–7.6. Photoperiod followed natural conditions. We monitored water quality parameters daily (Table 1).

2.2. Diet Formulation

Two dietary treatments were used:

1. Control diet: Standard compound feed with 100% krill meal as protein source.
 2. Experimental diet: Compound feed with 25% replacement of krill meal by big-scale sand smelt meal.
- Fish were fed to apparent satiation twice daily. Feed intake was recorded to calculate the feed conversion ratio.

2.3. Growth Performance Indicators

Control fish weighing (30 fish per tank) was performed every 10 days. The following parameters were calculated:

- Final body weight (g)
- Specific growth rate: $SGR = 100 \times [\ln(W_2) - \ln(W_1)] / t$

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- Feed conversion ratio: $FCR = \text{feed intake} / \text{weight gain}$
- Survival rate (%)
- Fulton's condition factor: $K = 100 \times W / L^3$

Table 1: Water quality parameters recorded during the study period

Date	Water temperature	Oxygen, mL/L	Saturation, %	PH	NO ₂	NO ₃	NH ₃ -NH ₄
12.07.2026	20.6	7.2	79.0	6.0	0	5.0	0.2
15.07.2026	21.6	7.8	83.0	8.0	0	0	0
18.07.2026	20.8	9.6	108.0	6.0	0.1	20.0	2
21.07.2025	21.8	10.4	117.0	7.0	0	0	0.3
24.07.2025	21.9	10.1	112.0	8.0	0	0	0
25.07.2025	22.5	8.9	93.0	7.4	0.1	10.0	0.5
28.07.2025	24.6	99.0	103.0	7.8	0.1	5.0	0.1
30.07.2025	23.1	9.8	106.0	7.6	0.1	10.0	0.4
01.08.2025	23.8	9.6	103.0	7.6	0	10.0	0
29.08.2025	25.1	9.9	102.0	7.0	0.2	20.0	0.4
01.09.2025	25.9	11.8	121.0	6.0	0.2	20.0	0.5
08.09.2025	24.8	8.7	102.0	6.7	0.2	0.1	0
15.09.2025	22.8	8.6	100.0	7.0	0.1	20.0	0.3
18.09.2025	22.2	8.8	96.0	7.4	0.2	20.0	0.7
22.09.2025	22.1	9.7	100.0	6.4	0.2	10.0	0.7
25.09.2025	19.6	9.7	103.0	7.4	0.2	20.0	0.5
08.10.2025	19.5	11.9	101.0	7.2	0.1	5.0	8.0
13.10.2025	18.4	9.8	107.0	8.0	0.1	40.0	0.1

2.4. Biochemical Analysis

At the end of the experiment, we analyzed muscle tissue for crude protein by the Kjeldahl method, crude fat by Soxhlet extraction, and ash content by combustion in a muffle furnace.

2.5. Statistical Analysis

Data are presented as mean $\pm$ SD. We assessed normality using the Shapiro–Wilk test and homogeneity of variances using Levene's test. We used two-way ANOVA (diet $\times$ time) to evaluate effects on body mass and condition factor. We used one-way ANOVA for final growth parameters and biochemical composition. When we found significant differences, we applied Tukey's HSD post hoc test. We set the significance level at $P < 0.05$. Analyses were performed in Python.

3. RESULTS

3.1. Growth Performance and Survival

The experimental diet significantly improved growth performance compared with the control diet (Table 2).

Table 2: Fish breeding indicators of juvenile Russian sturgeon

Parameters	Control	Experiment	P-value
Initial weight, g	30.0 $\pm$ 2.0	30.0 $\pm$ 2.0	n.s.
Final weight, g	154.6 $\pm$ 25.3 ^a	160.4 $\pm$ 25.9 ^b	0.032
SGR, %/day	1.04 $\pm$ 0.01 ^a	1.06 $\pm$ 0.01 ^b	0.018
Survival rate, %	84.4 $\pm$ 2.1 ^a	87.8 $\pm$ 1.8 ^b	0.041
FCR	1.39 $\pm$ 0.07 ^a	1.31 $\pm$ 0.08 ^b	0.028
Fulton's condition factor	0.47 $\pm$ 0.07 ^a	0.56 $\pm$ 0.05 ^b	

Values are mean $\pm$ SD, n = 30 per group. Values with different superscripts in a row differ significantly at $P < 0.05$. n.s. – not significant.

Table 3: Main biochemical parameters of juveniles at the end of breeding

Parameters (%)	Control	Experiment	P-value
Crude proteins	16.3 $\pm$ 0.4	16.5 $\pm$ 0.5	0.234
Crude fat	2.98 $\pm$ 0.30	3.46 $\pm$ 0.25	0.112
Ash	1.04 $\pm$ 0.10	1.98 $\pm$ 0.15	0.067

Non significant differences in protein, fat, and ash content were observed between groups ($P > 0.05$). The slight increase in protein and fat in the experimental group suggests a trend toward improved nutrient retention.

3.3. Biochemical Parameters

The biochemical parameters of juveniles including crude proteins, crude fat and ash at the end of breeding season in experimental fish did not differ that the control group (Table 3).

Final body weight in the experimental group was 4.6% higher than in the control. Two-way ANOVA confirmed significant effects of diet group ($P = 0.0000$), time ($P = 0.0000$), and their interaction ($P = 0.0061$) on body mass dynamics, indicating divergent growth trajectories between treatments (Fig. 1-3). Survival rate was significantly ($P < 0.05$) higher in fish fed the experimental diet (Fig. 4), demonstrating no negative impact on fish health.

3.2. Feed Efficiency and Condition Factor

Feed conversion ratio was 6% lower in the experimental group, indicating superior feed utilization efficiency. Fulton's condition factor tended to be higher in the experimental group, though the difference was not statistically significant ($P = 0.089$).

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4. DISCUSSION

The present study demonstrates that partial replacement of krill meal with fish meal produced from large-scale sand smelt (*Atherina boyeri*) significantly improved the growth performance of juvenile Russian sturgeon (*A. gueldenstaedtii*) cultured under recirculating aquaculture system (RAS) conditions. Fish receiving the experimental diet showed higher final body weight, improved specific growth rate, lower feed conversion ratio, and higher survival than the control group, with no adverse effects on biochemical composition. These findings indicate that large-scale sand smelt meal can effectively substitute part of the conventional marine protein source without compromising fish health or growth performance.

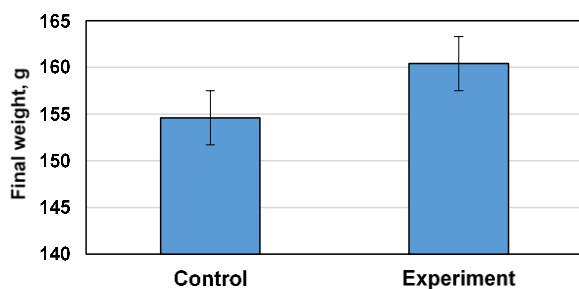


Fig. 1: Final weight of juvenile Russian sturgeon. Shows higher final body weight in the experimental group after 120 days.

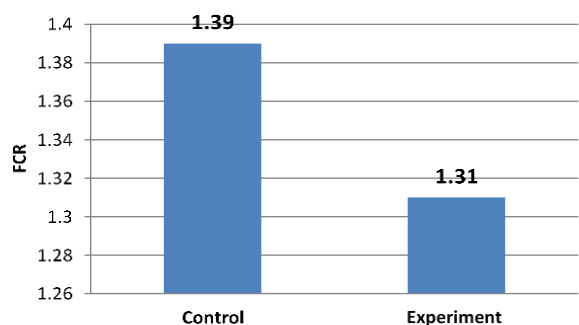


Fig. 2: Feed conversion ratio by dietary treatment. Demonstrates improved feed efficiency in the experimental group.

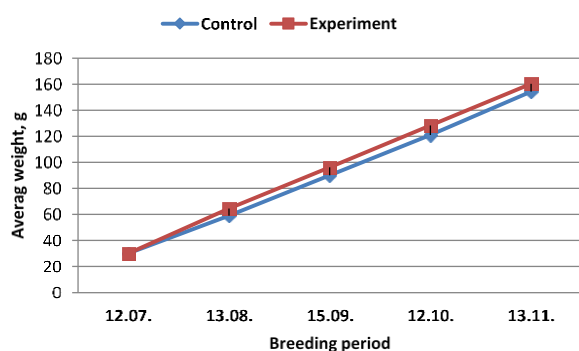


Fig. 3: Growth dynamics over 120 days. Illustrates consistent growth advantage of the experimental diet throughout the trial.

approximately 6%, indicating more efficient utilization of dietary nutrients. This improvement is particularly relevant for commercial RAS facilities, where feed expenses make up the largest share of operational costs. Consequently, using locally produced fish meal from large-scale sand smelt may provide both biological and economic advantages for sturgeon producers (Engle, 2010a; Kabir et al., 2026).

The significantly higher survival rate recorded in fish fed the experimental diet further confirms that partial substitution of krill meal did not induce physiological stress or impair fish welfare. This conclusion is additionally

Feed quality remains one of the most important determinants of production efficiency in intensive sturgeon aquaculture. Marine-derived protein ingredients, particularly fish meal and krill meal, are traditionally regarded as the nutritional standard because of their high digestibility and balanced amino acid composition (Hua et al., 2019; Bagheri et al., 2026). However, rising prices and limited availability have intensified the search for sustainable alternatives. Numerous studies have shown that partially replacing traditional protein sources with locally available raw materials can reduce production costs while maintaining growth performance in sturgeons and other carnivorous species. The present results support this concept and demonstrate that fish meal prepared from big-scale sand smelt represents a promising alternative ingredient for commercial sturgeon feeds (Hardy, 2010; Tacon & Metian, 2015; Trejo-Escamilla et al., 2017; Sayed Hassani et al., 2021).

The superior growth observed in the experimental group is likely associated with the favorable nutritional characteristics of big-scale sand smelt. Previous studies have reported that small pelagic fish species contain high concentrations of digestible protein while maintaining relatively low lipid content, thereby reducing oxidative deterioration during feed storage (Hayes, 2018). In addition, the balanced amino acid and fatty acid profile of forage fish meal may promote more efficient protein utilization and tissue deposition, ultimately improving weight gain and feed conversion efficiency in juvenile sturgeons. Although the present study did not directly analyze amino acid composition, the observed biological responses strongly suggest that the experimental diet had adequate nutritional quality (Gatlin et al., 2007).

Feed conversion ratio is among the most important economic indicators in commercial aquaculture because even small improvements can substantially reduce production costs under intensive farming conditions. In the present experiment, replacement of 25% of krill meal reduced feed conversion ratio by

supported by the absence of statistically significant differences in muscle biochemical composition between dietary treatments. Protein, lipid, and ash contents remained within comparable ranges, indicating that replacing marine protein sources did not adversely affect nutrient deposition or the overall physiological condition of juvenile sturgeon. Maintenance of normal biochemical composition is an important indicator of feed safety and nutritional adequacy in aquaculture nutrition studies.

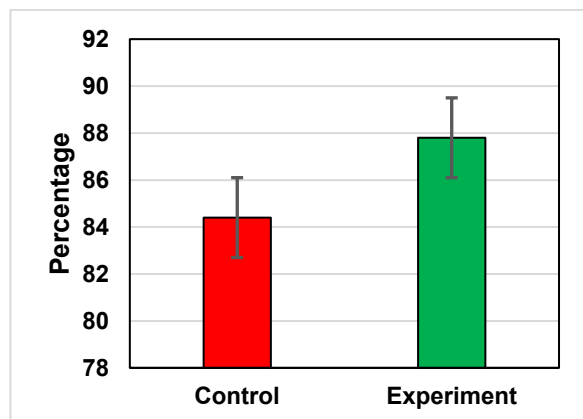


Fig. 4: Survival rate (%) of juvenile Russian sturgeon fish in control and experimental groups showing a significant difference ($P < 0.05$).

An important finding of the present study is the significant interaction between dietary treatment and cultivation time observed in the two-way ANOVA. This

Several limitations should be acknowledged. The experiment ran for 120 days and evaluated only one dietary replacement level. Furthermore, the study did not investigate amino acid composition, fatty acid profile, digestibility coefficients, or digestive enzyme activity. Future studies should examine different inclusion levels of large-scale sand smelt meal, evaluate long-term production performance to market size, and investigate the physiological, biochemical, and molecular mechanisms underlying the observed improvements in growth and feed utilization. Additional economic analyses comparing feed manufacturing costs and production profitability would further support the commercial application of this dietary strategy (Engle, 2010b).

Recent studies on sturgeon nutrition further support the importance of using moderate rather than complete replacement levels when developing alternative protein sources. In juvenile Siberian sturgeon, replacing 10–30% of fish meal with rapeseed meal did not negatively affect growth performance, survival, health status, or muscle composition, showing that partial substitution can be implemented successfully when the alternative ingredient's nutritional characteristics are appropriate (Wnęk-Auguścik et al., 2024). A subsequent study in hybrid sturgeon similarly showed that replacing less than 50% of fish meal with rapeseed meal did not compromise overall fish health, whereas increasing replacement levels progressively reduced final body weight, weight gain, and survival (Zhang et al., 2025). These findings are particularly consistent with the present results, where a relatively moderate 25% replacement of krill meal with big-scale sand smelt meal improved growth and feed utilization rather than reducing performance, as is often observed at high inclusion levels. The positive response observed in the present experiment therefore suggests that the nutritional value of big-scale sand smelt meal may allow it to be incorporated into sturgeon diets at moderate levels without disrupting the balance of essential nutrients.

Recent sturgeon feeding trials have also shown the importance of maintaining adequate amino acid availability when replacing marine protein sources. Complete replacement of fish meal with cottonseed protein concentrates in *A. schrenckii* reduced weight gain and feed efficiency, decreased digestive enzyme activity, altered essential amino acid deposition, and changed hepatic metabolism (Wang et al., 2023). Similarly, completely replacing fish meal with soybean protein concentrates in hybrid sturgeon impaired growth and increased feed conversion ratio when the diet was not supplemented with methionine; however, methionine supplementation restored growth performance and protein utilization to levels comparable with the fish-meal control (Li et al., 2025). These results indicate that the biological effectiveness of an alternative protein ingredient depends strongly on its amino acid profile and the degree of replacement. In contrast, the improved growth performance and reduced feed conversion ratio observed in the present study suggest that the 25% inclusion of big-scale sand smelt meal provided sufficient high-quality protein without creating a major amino acid limitation. Although the present experiment did not directly determine amino

interaction indicates that the beneficial effect of the experimental diet became more pronounced as fish developed, suggesting cumulative improvements in nutrient utilization throughout the culture period rather than only transient responses during early growth. Such long-term positive effects increase the practical value of the proposed feed formulation for commercial aquaculture.

Beyond its biological effectiveness, using large-scale sand smelt has important ecological and economic implications. This species is commonly regarded as a low-value commercial fish and is frequently harvested as bycatch in the Caspian Sea. Converting this underutilized resource into high-quality aquafeed ingredients improves the use of regional fishery resources, reduces dependence on imported krill meal, and supports the development of domestic feed production. This approach aligns with current principles of sustainable aquaculture and the circular bioeconomy, which emphasize maximizing the value of locally available biological resources while minimizing waste and import dependence.

acid composition, the growth response and improved nutrient utilization provide indirect evidence that the experimental diet was nutritionally adequate.

Recent investigations using other animal-derived and aquatic by-product ingredients provide further support for the present findings. Partial replacement of fish meal with shrimp waste meal in juvenile beluga sturgeon did not negatively affect growth, carcass composition, or digestibility at replacement levels of 15–20%, while several immune parameters were actually enhanced (TaHERi et al., 2025). This shows that protein sources from underutilized aquatic biomass can provide nutritional benefits while also improving resource utilization. Comparable results have been reported for other aquaculture species, where marine proteins recovered from processing-water streams maintained growth and welfare performance comparable with conventional fish meal (Costa-Pierce et al., 2022). In addition, fishery and aquaculture by-products have recently been shown to enable substantial reductions in wild-caught fishmeal without necessarily compromising growth or health, supporting the broader concept of circular utilization of aquatic resources (TaHERi et al., 2025). Therefore, these results extend current evidence by demonstrating the potential of a locally available Caspian fish resource, *Atherina boyeri*, as a functional ingredient for sturgeon feed rather than simply a conventional fishery product.

The observed improvements in growth and feed efficiency also align with recent evidence that alternative protein ingredients can positively affect physiological performance when included at nutritionally appropriate concentrations. Dietary substitution of fish meal with *Chlorella vulgaris* in Siberian sturgeon improved final body weight and weight gain and was accompanied by enhanced digestive enzyme activity, antioxidant capacity, and immune responses (Bayati et al., 2025). Likewise, optimizing dietary protein concentration in juvenile hybrid sturgeon shows that feed formulation strongly influences both growth and immune-related physiological responses, emphasizing the importance of matching dietary protein supply to the requirements of rapidly growing fish (Wang et al., 2024). Other recent studies show that alternative protein ingredients can replace a substantial proportion of fish meal without adverse effects when digestibility and nutritional balance are maintained, although excessive inclusion may negatively affect feed intake, nutrient digestibility, or physiological condition (TaHERi et al., 2025). This experiment follows this general pattern, with the 25% replacement level producing a favorable response while avoiding the adverse effects reported at higher replacement levels in several sturgeon and other carnivorous fish species. This supports the hypothesis that the effectiveness of big-scale sand smelt meal is associated not only with its protein content but also with the compatibility of its overall nutritional characteristics with the requirements of juvenile Russian sturgeon.

From a practical perspective, the present findings are particularly relevant to intensive RAS production, where feed efficiency directly influences production costs and the economic sustainability of farming operations. Recent research on Russian sturgeon cultured in RAS has confirmed that these systems can efficiently convert dietary nutrients into fish biomass and that feed formulation can substantially influence nutrient transfer and utilization (Wang et al., 2024). The approximately 6% improvement in feed conversion ratio observed in the present study may therefore have considerable practical importance when extrapolated to commercial-scale production. Moreover, using a locally available fish resource could reduce dependence on imported marine protein ingredients and potentially shorten feed-supply chains. Recent research on alternative aquafeed ingredients increasingly emphasizes combining biological performance with resource efficiency and circularity, rather than evaluating replacement ingredients solely on growth parameters (TaHERi et al., 2025). From this perspective, converting underutilized regional fish biomass into feed for high-value Russian sturgeon represents a potentially valuable circular-bioeconomy strategy. However, further studies should quantify the amino acid and fatty acid composition of big-scale sand smelt meal, determine apparent digestibility coefficients, assess feed manufacturing characteristics, and compare the full production cost of experimental and conventional diets before recommending large-scale commercial implementation.

Overall, the findings show that partially replacing krill meal with big-scale sand smelt meal is a biologically effective, economically promising, and environmentally sustainable approach to improving the efficiency of Russian sturgeon culture in recirculating aquaculture systems.

5. CONCLUSION

The study confirms that replacing 25% krill meal with large-scale sand smelt meal in compound feeds significantly improves growth performance and feed efficiency in juvenile Russian sturgeon reared in RAS. Statistical analysis confirmed significant dietary effects on key aquaculture performance indicators. The results support using locally available fish resources in sturgeon feed formulations to reduce feed costs, decrease dependence on imported marine ingredients, and enhance the sustainability of commercial aquaculture.

Declarations

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Ethics Statement: The study was conducted in accordance with generally accepted bioethical principles for the use of animals in scientific research. Throughout the experiment, we took all necessary measures to ensure the welfare of the fish and minimize stress.

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