



Enrichment of *Artemia* Nauplius with Cyanobacterium *Arthrospira platensis* ZTS-2024 for Feeding Young Russian Sturgeon (*Acipenser gueldenstaedtii* Brandt, 1833)

Kenzhegul Bolatkhan,¹ Damys Salauat,¹ Saule M. Shalgimbayeva,¹ Nurzia R. Akmukhanova,¹ Bolatkhan K. Zayadan^{1,*} Aidana Askar¹ and Mehmet Gökoğlu²

Abstract

Early larval stages of sturgeon are highly sensitive to feed quality, and enrichment of live feed represents a key strategy for improving survival and growth performance. This study aimed to evaluate the effects of enriching *Artemia parthenogenetica* nauplii with the cyanobacterium *Arthrospira platensis* ZTS-2024 on the growth parameters and physiological conditions of juvenile Russian sturgeons (*Acipenser gueldenstaedtii*). *Artemia* nauplii were enriched using a two-step bioencapsulation protocol and subsequently fed to sturgeon larvae under controlled conditions. Growth dynamics, survival rate, biochemical composition, and muscle histology were assessed. Enriched *Artemia* exhibited superior nutritional quality, which contributed to enhanced growth efficiency in larvae. During the first week post-hatching, larvae fed enriched live feed exhibited an approximately 30% increase compared with the control group, accompanied by elevated muscle protein and lipid levels and improved muscle fiber organization. Despite extensive research on *Artemia* enrichment strategies, limited information exists on the use of region-specific *Arthrospira* strains for the early feeding of Russian sturgeons. The findings of the present study indicate that enrichment of *Artemia* nauplii with *Arthrospira platensis* ZTS-2024 represents an effective approach to improving growth performance, biochemical composition, and muscle tissue development during early sturgeon ontogeny.

Keywords: Russian sturgeon; Effect of *Arthrospira platensis* ZTS-2024; Growth and biochemical composition of *Artemia* nauplii; *Artemia parthenogenetica*; Larval nutrition.

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1. Introduction

Sturgeon aquaculture has expanded significantly to support the restoration of wild populations, the preservation of genetic diversity, and meeting market demand for delicacy products. Among the commercially valuable sturgeons, the Russian sturgeon (*Acipenser gueldenstaedtii*) is critically vital due to its role in the black caviar industry,^[1,2] recognized for its high-quality caviar and lean meat yet is classified as Critically Endangered on the IUCN Red List, making the development of reliable aquaculture biotechnologies imperative.^[3]

A significant issue in sturgeon larviculture is the elevated mortality rate during the shift from endogenous to exogenous feeding, as their natural euryphagous diet, consisting of diverse benthic invertebrates, is challenging to reproduce in

captivity.^[4,5] During the early larval stage of sturgeon, there is a critical phase when the quality of their nutrition becomes essential due to their rapid growth, high metabolic needs, and underdeveloped digestive systems. This vulnerability arises from an underdeveloped digestive system, whereby immature pancreatic and intestinal functions require dietary enzymes sourced from live prey.^[6,7]

Artemia nauplii (*Artemia* Leach, 1819) are a standard live feed in sturgeon larviculture owing to their appropriate size, mobility, and high digestibility.^[8,9] For sturgeon, live feed is typically supplied until fry reaches 1-2 g.^[10] However, the natural nutritional profile of *Artemia* is often insufficient to fully meet the physiological requirements of sturgeon larvae, lacking optimal amino acid composition, sufficient dietary energy density, and specific bioactive compounds required for muscle development and metabolic regulation.^[11,12]

To overcome these deficiencies, bioencapsulation (enrichment), the process of feeding nutrient-rich supplements

¹Faculty of Biology and Biotechnology, Al-Farabi Kazakh National University, 71 Al-Farabi, Almaty, 050038, Kazakhstan

²Akdeniz university, Fisheries Faculty, Antalya, 07058, Turkey

*Email: zbolatkhan@gmail.com (B. K. Zayadan)

to *Artemia* nauplii prior to their use as feed, is a common strategy to overcome these limitations. This method aims to improve the survival and growth of larvae. However, outcomes can be inconsistent. For instance, Iranian scientists revealed that bioencapsulation provided only a marginal survival advantage (5%) and no significant growth enhancement for Persian sturgeon (*Acipenser persicus*) larvae,^[13] highlighting the need for more effective enrichment protocols.

In recent years, there has been a heightened focus on enhancing compound feeds in aquaculture through the addition of natural biologically active compounds.^[14] Microalgae have emerged as a promising resource as a functional bioactive supplement in animal feeds.^[15,16] As the costs of fish feeds rise, incorporating microalgal biomass into aquafeeds presents a strategic method to mitigate aquaculture production expenses. The nutritional profile of microalgal biomass, which includes essential amino acids, polyunsaturated fatty acids, vitamins, and antioxidants, plays a critical role in the growth, and metabolic regulation of larvae.^[17-20] This approach aims to find an optimal balance between feed quality and economic efficiency, prompting producers to innovate feed formulations and enhance feeding management techniques.^[21] Furthermore, integrating microalgae into *Artemia* bioencapsulation processes may improve the nutritional value of live feed while promoting sustainability and cost-effectiveness, offering a superior solution to address nutritional challenges faced during the early developmental stages of sturgeon larvae.^[22,23]

Among the diverse microalgal taxa investigated to date, *Spirulina platensis* (syn. *Arthrospira*) occupies a distinctive position. This phototrophic, filamentous cyanobacterium is composed of multicellular helical trichomes and is classified within the *Cyanophyceae*.^[24] Its biomass contains an unusually rich ensemble of minerals, vitamins, carotenoids, tocopherols, phenolic acids, and high-quality proteins. Such biochemical abundance forms the basis for a wide spectrum of biological activities, and *Spirulina* has long been incorporated as a dietary supplement in both human nutrition and animal husbandry.^[25] Naturally, the organism thrives in alkaline, saline lakes of subtropical and tropical regions across the Americas, Mexico, Asia, and Central Africa, where environmental pressures appear to shape its metabolic diversity.^[26]

A considerable body of research attributes to *Spirulina platensis*—and particularly to its hallmark pigment—protein complex, C-phycocyanin—a broad array of physiological effects, including antioxidant, anti-diabetic, antihypertensive, antiviral, immunomodulatory, hepatoprotective, renoprotective, neuroprotective, and antigenotoxic actions.^[27] Some clinical and preclinical observations support these functional claims. Experimental studies on animal models^[28] indicate that *Spirulina* supplementation significantly reduces liver oxidative stress, decreases lipid peroxidation, normalizes antioxidant enzyme activities, and suppresses pro-

inflammatory mediators. Specifically, *Spirulina* and isolated phycocyanin have been found to lower mitochondrial reactive oxygen species production in liver and immune cells, thus alleviating inflammation-related liver damage and slowing chronic liver disease progression.

The cyanobacterium *Arthrospira platensis* (*Spirulina*) is a promising enrichment agent due to its high protein content, balanced amino acids, and abundance of micronutrients and antioxidants. This profile aligns with the specific demands of sturgeon larvae for substrates that support rapid somatic growth and myogenesis. Furthermore, evidence^[29] suggests that the inclusion of microalgae, such as *Tetraselmis* sp. in *Artemia* diets can positively influence the gut microbiome of nauplii, leading to increased bacterial diversity and a reduction in harmful bacteria. The secondary benefit of enrichment, specifically enhanced live feed health and stability, necessitates further investigation in conjunction with direct nutritional enhancement.

Despite the increasing interest in *Spirulina*-based feed additives, most research has concentrated on generic, commercially available strains rather than exploring novel, region-specific variants. The biochemical profile and functional properties of cyanobacteria, including *Arthrospira*, are susceptible to variations based on their geographic origins and environmental conditions, leading to differences in their nutrient profiles. This indicates that specific strains of *Arthrospira* may offer unique metabolic advantages and higher levels of beneficial compounds. However, the potential use of these distinctive, region-adapted strains for the bioencapsulation of *Artemia* in sturgeon larviculture has been insufficiently explored, highlighting a gap in current aquaculture research that warrants further investigation.

To address a knowledge gap in biotechnology, a novel cyanobacterial strain, *Arthrospira platensis* ZTS-2024, was isolated from the Balkhash–Alakol Basin in southeastern Kazakhstan, indicating its potential as a local biological resource. The research focused on using this strain as an enrichment agent for *Artemia parthenogenetica* nauplii and its effects on the early development of Russian sturgeon. The objectives included: (i) characterizing the productivity and biochemical composition of *Arthrospira platensis* ZTS-2024; (ii) assessing its effects on the survival and growth of *Artemia* nauplii; (iii) analyzing the influence of enriched *Artemia* on juvenile Russian sturgeon's growth and muscle tissue composition; and (iv) conducting histological analyses of sturgeon muscle tissue for morphological differences related to the dietary treatment.

2. Materials and methods

2.1 Cultivation of the cyanobacteria strain *Arthrospira platensis* ZTS-2024

The cyanobacterium strain *Arthrospira platensis* ZTS-2024, used in this study, was obtained from the collection of phototrophic microorganisms at the department of biotechnology of Al-Farabi Kazakh National University. It

was originally isolated from the saline southeastern region of Balkhash Lake (Lepsinsky district, Zhetysu region, Kazakhstan), where water temperature is 24–29 °C, pH 7.0–9.0 during summer. The *Arthrospira platensis* ZTS-2024 strain was chosen based on its growth rate, biomass accumulation, and capacity to accrue proteins, lipids, carbohydrates, and pigments. It is a filamentous, multicellular organism. The trichomes consist of vegetative cells and possess a helical structure, without a sheath.

The first stage of the experiment involved the preparation of a suspension of the cyanobacterium *Arthrospira platensis* ZTS-2024, conducted in the laboratory of “ALGABIOTECH” at the international research center of Al-Farabi Kazakh National University. The strain was cultivated in Zarrouk's medium. Pre-cultures were cultivated in sterilized glass flasks (100–500 mL) at 28–30 °C under continuous illumination (50–200 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$) from fluorescent lamps. Culture purity was assessed microscopically after 4–7 days. The development and purity of the culture were microscopically assessed using immersion oil at a 100x magnification. For large-scale biomass production, a laboratory photobioreactor was used under the same temperature and light regime. The increase in biomass was evaluated by measuring the variation in optical density of the suspension at a wavelength of 750 nm with an SF-2000 spectrophotometer. The harvested biomass was used for biochemical analysis and *Artemia* enrichment.

2.2 Analysis of the biochemical composition of the obtained cyanobacterial biomass *Arthrospira platensis* ZTS-2024

1. Protein determination — modified Lowry method^[30]
2. Carbohydrate determination — Dubois method^[31]
3. Lipid determination — Bligh and Dyer method^[32]

2.3 Cultivation and enrichment of *Artemia* nauplii from populations of *Artemia* sp.

The enrichment experiment was conducted at the aquarium laboratory of the “KKH KOLLAR” fish farm (Almaty Region, Kazakhstan) to enrich *Artemia* sp. nauplii with the cyanobacterium *Arthrospira platensis* ZTS-2024 for subsequent feeding of sturgeon larvae. Cysts were collected from the South Aral Sea (Kazakhstan) and incubated following standard methodology.^[33]

The experiment followed a replicated parallel-group design. Two experimental treatments were established: a control group fed unenriched *Artemia* nauplii and an experimental group fed *Artemia* nauplii enriched with *Arthrospira platensis* ZTS-2024. Each treatment was conducted in three independent replicates. Each replicate consisted of 150 larvae at the start of the experiment. Growth and survival assessments were performed on randomly sampled subsets of 40–50 individuals per replicate at each measurement point. A key prerequisite for achieving stable results is the maintenance of environmental conditions that closely approximate the organism's natural habitat, together

with strict control of sanitary parameters throughout the cultivation process. When *Artemia* nauplii are used as live feed, a significant risk arises from the transmission of pathogenic microflora associated with residual egg shells remaining in the culture medium. To mitigate this risk, two effective measures were applied: optimization of *Artemia* population density and the timely removal of dead and empty cyst shells using flotation techniques.

The selection of the two *Arthrospira platensis* ZTS-2024 enrichment concentrations was based on a two-step bioencapsulation strategy. The removal of shells and unhatched cysts, as well as the primary enrichment process, was carried out over a one-hour period (at a 25-hour naupliar age) in water maintained at +28 °C with continuous aeration. A higher initial concentration (0.9 g·dm⁻³) was applied to ensure rapid ingestion and effective gut loading of *Arthrospira* biomass by *Artemia* nauplii during the initial enrichment phase. A further enrichment was conducted^[33,34] after 6 hours using *Arthrospira platensis* ZTS-2024 at a concentration of 0.12 g/dm³, while preventing excessive particle aggregation, deterioration of water quality, and stress-related mortality of nauplii. The average water conditions during the experiment were a dissolved oxygen level of 6.0–7.0 mg/dm³ (controlled with EHEIM-100 compressors) and a water temperature of +17 °C. Temperature and dissolved oxygen concentrations were monitored hourly using a portable measuring device (USA). A full chemical water analysis was done with standard methodologies.^[35] This approach allows efficient nutrient incorporation while maintaining high *Artemia* survival. After 12 hours of bioencapsulation, nauplii survival exceeded 96%, and their size increased by 30%.

The feeding frequency of 20–24 times per day during the earliest larval stages was intentionally applied to mimic near-continuous natural feeding conditions and to compensate for the limited stomach capacity and rapid gut evacuation characteristic of newly hatched sturgeon larvae. At this stage, larvae exhibit an underdeveloped digestive system and rely on frequent small feed portions to ensure continuous nutrient availability and efficient digestion. Similar high-frequency feeding regimes have been reported as effective in early sturgeon and marine fish larviculture, where continuous or semi-continuous live feed supply significantly improves survival and growth rates. As larval body mass increased and digestive capacity improved, feeding frequency was gradually reduced to 10–12 times per day.

2.4 Hydro-chemical parameters of aquarium water (juvenile Russian sturgeon).

Water characteristics are temperature: 21 °C; dissolved oxygen: 7.0g/L; pH: 7.5; NH₃: 5±7g/L; NHO₂: 0.01±0.004g/L. The experiment lasted 10 weeks and involved three repetitions. The weight gain of nauplius and juvenile sturgeon was calculated using the formulas:

1. Total weight gain (A):

$$A = M_i - M_f$$

M_i - initial mass (g)

M_f - final mass (g)

2. Average daily growth (C):

$$C = \frac{M_f - M_i}{T}$$

T - duration of the experiment (days).

3. Relative gain:

$$\text{Relative gain} = \frac{M_f - M_i}{M_i} \times 100\%$$

2.5 Analysis of the biochemical composition of *Artemia* nauplii

The following biochemical parameters were assessed: dry matter content, ash, protein (without mineralization), free amino acids, lipids, and carbohydrates according to AOAC methods.^[36] The dry matter was estimated using the gravimetric method after drying at 105 °C, and the ash at 500 °C. The Biuret method^[37] was used to examine protein concentration in samples in an alkaline extract without mineralization. Protein concentration in the samples was determined by a spectrophotometric method after alkaline extraction, using a calibration curve constructed with bovine serum albumin as the standard, following the general procedures described for protein analysis.^[38] The Bertrand method^[39] was used for quantitative determination of glucose in an extract. The matter of lipids was measured using the extraction-weight method, which involved a binary mixture of chloroform and methanol in a 2:1 ratio.^[40]

Proximate composition analysis of *Artemia* nauplii and fish muscle tissue included the determination of moisture, dry matter, ash and organic matter, as well as protein, lipid and carbohydrate contents.^[41] Moisture-related parameters were expressed as a percentage of wet weight, while protein, lipid and carbohydrate contents were expressed as a percentage of dry weight. All measurements were performed in triplicate and results are presented as mean $\pm$ standard deviation.

2.6 Analysis of the biochemical composition of the trunk muscles of juvenile Russian sturgeon

The effectiveness of the feed used was assessed by the chemical composition of muscle tissue from the tail stalk of fish (total protein content without mineralization of samples by biuret reaction, determination of glucose in muscle tissue extracts via the Bertrand method, total lipids determined by accelerated solvent extraction followed by the gravimetric analysis method^[42] suggested by FAO manual.

The biochemical analysis^[43] was limited to proximate composition (protein, lipid, and carbohydrate), while detailed fatty acid profiling (DHA, EPA, ARA) and amino acid composition, emphasized as nutritionally important for aquaculture species^[44] were not evaluated due to methodological and instrumental limitations. These analyses are planned for future studies to provide a more complete

characterization of the nutritional value of enriched *Artemia* and fish tissues.

2.7 Histological analysis of trunk muscle tissue of sturgeon

For histological examination, 10 experimental and 10 control subjects were selected, which were previously immobilized. The trunk muscle samples were fixed in 10% neutral formalin for 24 hours. Sections with a thickness of 5 μ m were obtained using a rotary microtome (Kalstein, France). Staining was performed with hematoxylin and eosin (H&E) based on methodology. Microscopic analysis utilized a Leica DM 600 microscope (Leica c-Reichert, Germany), and micrographs were obtained using IS Capture software (Ambala Cantt, India).

2.8 Statistical analysis

All quantitative data are presented as mean $\pm$ SD. Normality of data distribution was assessed using the Shapiro–Wilk test, and homogeneity of variances was evaluated using Levene’s test. When assumptions of normality and homoscedasticity were met, differences between the control and experimental groups at individual time points were analyzed using an independent-samples Student’s t-test. If these assumptions were violated, the non-parametric Mann–Whitney U test was applied.

For time-dependent growth measurements (daily observations), temporal changes in growth parameters between groups were primarily evaluated using pairwise comparisons at corresponding time points. Differences were considered statistically significant at $p < 0.05$.

3. Results and discussion

3.1 Study of productivity and biochemical composition of cyanobacterium strain *Arthrospira platensis* ZTS-2024

To use cyanobacteria in biotechnology, screening producer strains is necessary. The productivity of a species primarily determines its potential for use in biotechnology. The most important productivity indicators for phototrophic microorganisms include growth rate, photosynthetic activity, and dry biomass yield. Therefore, the cyanobacterial strain *Arthrospira platensis* ZTS-2024 was screened for productivity. The maximum dry biomass of *Arthrospira platensis* ZTS-2024 was 3.85 g/L, indicating a relatively high growth rate. The measured biomass yield of 3.85 g/L at 30 °C indicated the highest productivity under the tested conditions (Fig. 1).

Generally, cyanobacteria primarily consist of proteins, lipids, and carbohydrates, which collectively account for 50–70% of their dry weight.^[44] These compounds are critical for cellular growth, development, repair, and functionality. Data on *Arthrospira platensis* ZTS-2024 were compared with literature sources (Table 1). A recent study by Senila^[45] demonstrated that the protein content was 46.7%. The elevated protein content of *Arthrospira platensis* ZTS-2024 enables its use as an alternative or supplement to fishmeal, which is

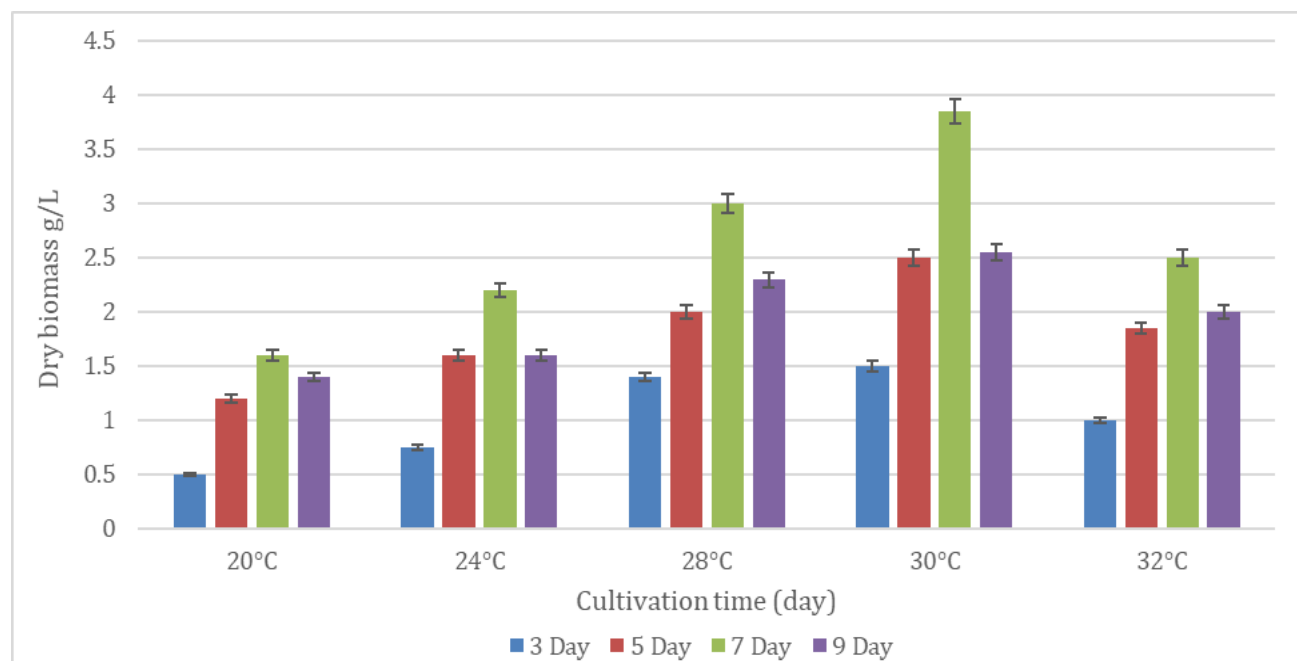


Fig. 1: Dry biomass accumulation of *Arthrospira platensis* ZTS-2024 during cultivation at different temperatures.

Table 1: Comparison of the biochemical composition of *Arthrospira platensis* ZTS-2024 biomass with literature data.

Biochemical metrics	<i>Arthrospira platensis</i>	<i>Spirulina platensis</i> by Méndez-Ancca ^[47]	<i>Spirulina platensis</i> by Senila ^[45]
Protein (%)	49.0 ± 1.7	52.0 ± 1.3	28.18 ± 0.33
Lipid (%)	16 ± 1.9	17 ± 1.4	0.71 ± 0.02
Carbohydrates (%)	12.08 ± 0.5	12.5 ± 1.5	62.07 ± 0.69

Note: Comparative biochemical composition (% dry weight) of *Arthrospira* (*Spirulina*) *platensis* in the present study and in selected literature sources.

among the costliest components of feed. The cyanobacterium *Arthrospira platensis* ZTS-2024 has the potential to lower feed costs and enhance the sustainability of aquaculture production.^[46] The carbohydrate content in *Arthrospira platensis* ZTS-2024 ($12.5 \pm 1.5\%$) was higher than in the study by Méndez-Ancca.^[47] The quality and quantity of dietary lipids are crucial for the normal development of fish.^[48] The lipid content of *Arthrospira platensis* ZTS-2024 (16%) in our experimental investigation was higher than the values reported and equivalent to the findings.

In the present study, the biochemical composition of *Arthrospira platensis* was characterized by a high protein content ($49.0 \pm 1.7\%$), along with relatively balanced levels of lipids ($16.0 \pm 1.9\%$) and carbohydrates ($12.08 \pm 0.5\%$). These values are in agreement with the data reported for *Spirulina platensis* by Méndez-Ancca.^[47] In contrast, the data reported by Senila^[45] indicate a markedly lower protein and lipid content and a substantially higher proportion of carbohydrates in *Spirulina platensis* biomass (Table 1).

Such differences reflect variability associated with strain-specific characteristics, culture conditions, and feeding regimes. Overall, the obtained results confirm the potential of

Arthrospira platensis as a high-protein and energetically valuable biomass source.

3.2 Effect of *Arthrospira platensis* ZTS-2024 on the growth parameters of *Artemia nauplii*

The ratio of the dry weight of the cysts to the wet biomass of the nauplii was 1:2.5, which shows that the cysts are of high quality. Histological sections of the cysts reveal the structural organization, consisting of an outer cuticular membrane, an inner cortical membrane, and a spongy chitinous envelope (Fig. 2A). The embryos, encased in a delicate membrane, began to emerge at a water temperature of 28 °C, which occurred 16-20 hours after incubation began, marking the beginning of the “umbrella stage” (Fig. 2B). When hydrated, the dark-pigmented outside envelope helps the cyst float on water and stimulates embryonic development. After 12 hours of enrichment, survival was significantly higher ($p < 0.05$) in the *Arthrospira*-enriched group compared to the control, which experienced a 10% mortality. The stage II nauplius of *Artemia* formed 36 hours after hatching from the cyst. At this stage, the nauplius exhibits active locomotion, with thoracic appendages and antennae undergoing development. The yolk sac is completely depleted, and the organism transitions to

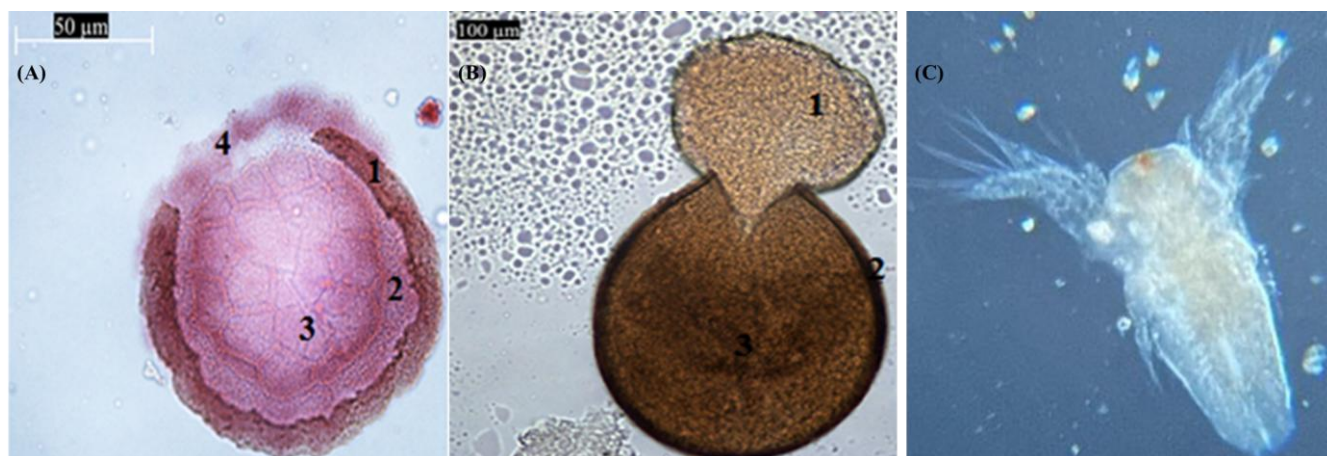


Fig. 2: (A) micrograph of a histological section of a cyst. 1- outer cuticular membrane; 2- cortical membrane; 3- chitinous envelope; 4- site of envelope rupture. Staining: Hematoxylin and Eosin (H&E). Magnification: $\times 40$. (B) micrograph of the exit of an *Artemia* embryo from a cyst. 1- embryonic mass; 2- outer dark-pigmented envelope. Scale bar = 100 μ m. (C) *Artemia* nauplius.

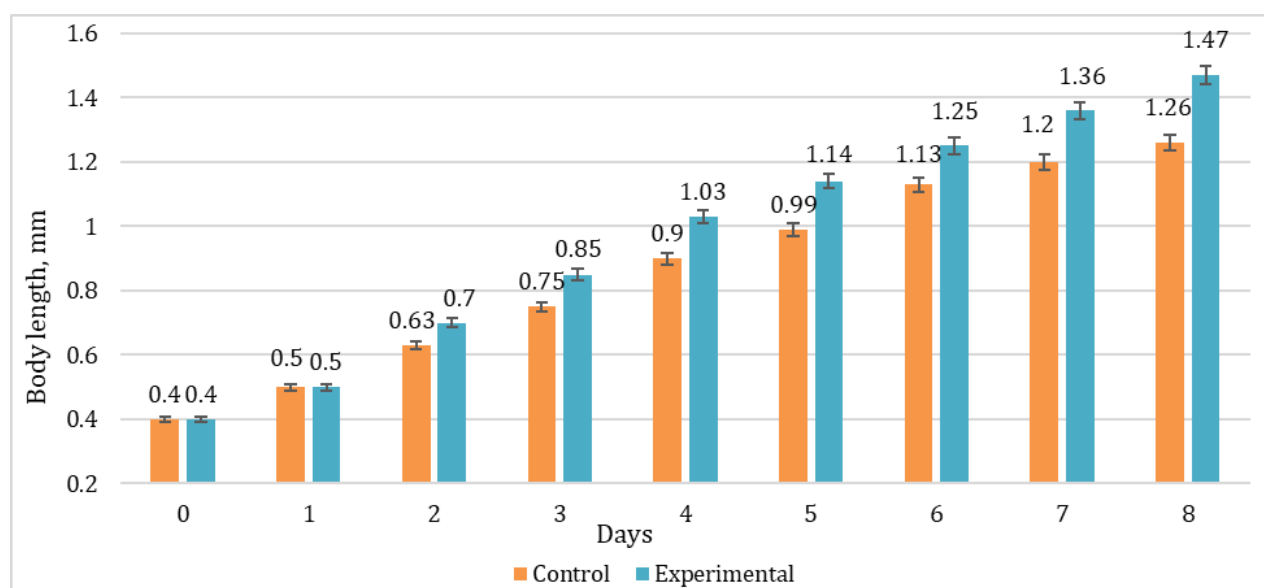


Fig. 3: Linear growth (body length, mm) of *Artemia* nauplii in the control and experimental groups over 8 days (mean $\pm$ SD, $n = 40$).

exogenous feeding, entering an active feeding phase (Fig. 2C).

No differences in body length were observed between the control and experimental groups during days 0–1 (0.40–0.50 mm).

From day 2 onward, the linear growth rate in the experimental group was higher than in the control group (0.70 mm vs. 0.63 mm). By day 8, body length reached 1.47 mm in the experimental group compared with 1.26 mm in the control group (Fig. 3). Overall, experimental feeding increased the linear growth of *Artemia* nauplii by approximately 17%.

During days 0–1, the body weight of *Artemia* metanauplii did not differ between the control and experimental groups (0.009 g). From day 2 onward, a greater increase in body weight was observed in the experimental group compared with the control group. By day 8, the body weight of the experimental group reached 0.050 g, exceeding that of the control group (0.039 g) (Fig. 4). Overall, the experimental conditions increased body weight accumulation in *Artemia* metanauplii by approximately 28%.

The present study shows higher mean body weight of *Artemia* metanauplii in the experimental group compared with the control group, resulting in a relative growth of 28.2% (Table 2).

These values slightly exceed the ranges reported in published literature, where relative growth typically varies between 15 and 25% under comparable rearing conditions (Table 2). The literature ranges summarize data from previous studies and reflect variability associated with differences in feeding regimes and culture conditions.

3.3 Biochemical composition of *Artemia* nauplii: protein, carbohydrate, and lipid content

Enrichment with *A. platensis* ZTS-2024 significantly altered the biochemical composition of *Artemia* nauplii.^[49] *Artemia* is a rich protein source (40%), and its amino acid composition determines the nutritional value of the crustacean. Several authors have studied the content of free amino acids depending on the stage of development of the crustacean, noting a stable

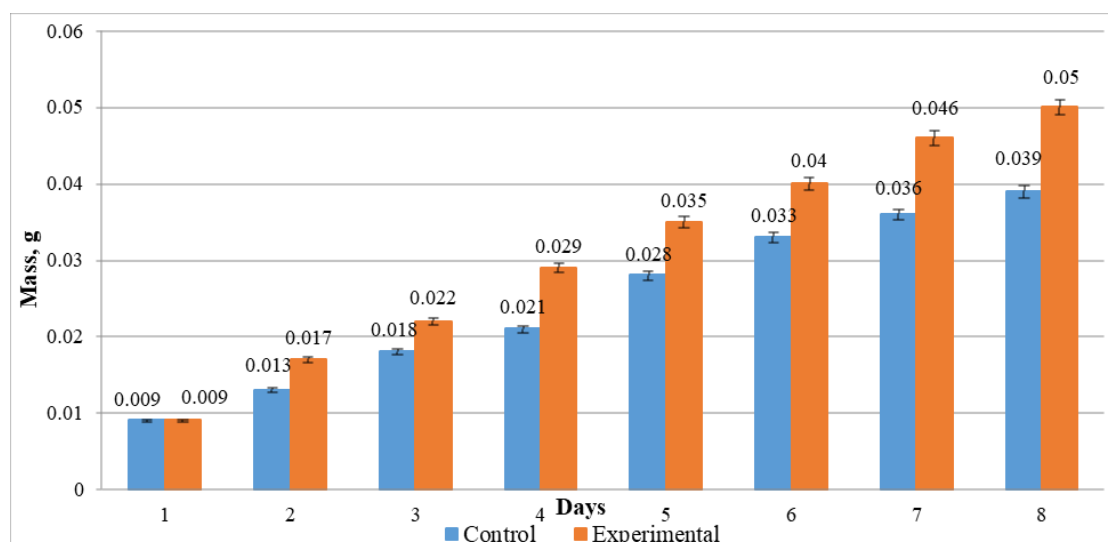


Fig. 4: Body weight parameters of *Artemia metanauplii* in the control and experimental groups after 8 days of rearing. (g; mean ± SD, n = 40).

Table 2: Body weight and relative growth of *Artemia metanauplii* in the control and experimental groups after 8 days of rearing.

Source	Control (g)	Experimental (g)	Relative growth (%)
The present study	0.039	0.050	28.2
Published literature	0.038 – 0.045	0.045 – 0.052	15 – 25

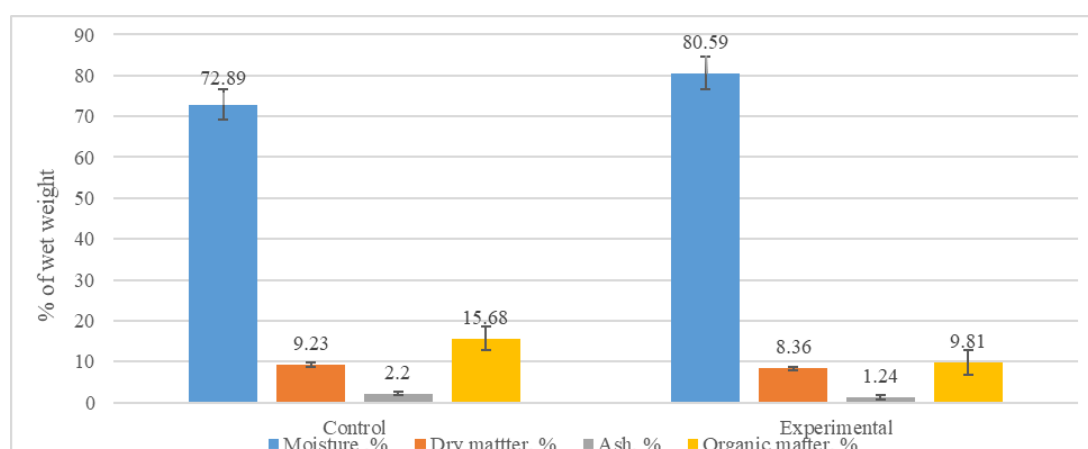


Fig. 5: Moisture, dry matter, ash and organic matter contents in *Artemia nauplii* of the control group (% of wet weight).

increase in their concentration because of autolytic proteolysis.^[50] Clegg and Conte conducted a qualitative analysis of carbohydrates isolated from *Artemia* cysts and found that 98% was trehalose disaccharide, and its content decreased during hatching.^[51] In addition, Clegg and Campagna suggest that trehalose ensures the resistance of animal cells to dehydration.^[52] Various sources describe the primary importance of lipids for current metabolic processes as an energy reserve, which plays an important role in biochemical reactions when the body exits the state of hydrobiosis.

Water, together with dissolved organic and mineral substances, constitutes the medium in which the main biochemical processes of the organism occur. A substantial proportion of water is associated with protein structures, ensuring the stability of protein molecules and their colloidal

state, whereas free water forms part of biological fluids. Consequently, an increase in moisture content may be accompanied by a relative decrease in the proportions of dry matter, ash, and lipids.

As shown in Fig. 5, the moisture content of *Artemia* nauplii in the experimental group was higher than that in the control group (80.59% and 72.89%, respectively). In contrast, the control group exhibited higher proportions of dry matter, ash, and organic matter. These differences are critical indicators of nutrient density, suggesting that the enrichment protocol altered the prey's biochemical profile.

The graph presents the main biochemical composition of *Artemia* biomass in the control and experimental groups (% of dry weight). Protein content was higher in the experimental group than in the control (15.05% vs. 12.35%), indicating an improvement in nutritional value (Fig. 6). Overall, the

experimental treatment favorably modified the biochemical profile of *Artemia* biomass, characterized by enhanced protein accumulation and reduced proportions of carbohydrates and lipids.

3.4 Effect of enriched *Artemia* nauplii on the growth of sturgeon larvae

The research focused on juvenile Russian sturgeon (*Acipenser gueldenstaedtii* Brandt, 1833), which had an average weight of 0.5g. The experimental group was given *Artemia* nauplii enriched with the spirulina *Arthrospira platensis* ZTS-2024, whereas the control group was fed unenriched nauplii. Feeding rates were adjusted based on observed consumption and standard larval rearing protocols for sturgeons. On the first day, the sturgeon fry's live feed did not surpass 20% of their body mass; consequently, the daily diet was raised to 50%. Significant differences in weight gain first became apparent on day 4-5 of the feeding trial. Feeding occurred 20 to 24 times daily at 100% live feed volume until the larva mass reached 60 mg. Following this, it dropped to 10–12 times per day with an increase in feed volume up to 8 times. Fig. 7 displays the growth trends of sturgeon larvae in experimental and control

groups over a 10-day period. Before feeding on the 10th day of the experiment, fish were caught and weighed. From each group, 40 to 50 species were weighed.

At the end of the experimental period, the final body weight of sturgeon larvae reached 1.10 g in the control group and 1.353g in the enriched-feed group. Based on the growth dynamics, the average daily gain (ADG) was approximately $0.06 \text{ g} \cdot \text{day}^{-1}$ in the control group and about $0.085 \text{ g} \cdot \text{day}^{-1}$ in larvae fed live enriched feed (Fig. 7).

The graph shows the biochemical composition of *Artemia* biomass in the control and experimental groups (% of dry weight). The proportion of protein was markedly higher in the experimental group than in the control (15.83% vs. 13.36%) (Fig. 8). In contrast, carbohydrate content decreased in the experimental group to 0.30%, compared with 0.78% in the control (Fig. 8).

Lipid content was also reduced in the experimental group (3.87%) relative to the control (5.86%) (Fig. 8). Overall, experimental feeding shifted the biochemical profile of *Artemia* biomass toward a protein-enriched composition, accompanied by a relative reduction in carbohydrate and lipid fractions.

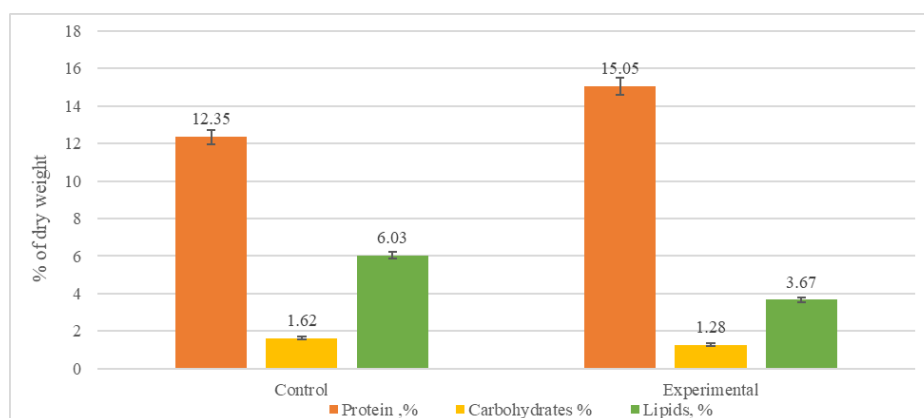


Fig. 6: The biochemical composition of *Artemia* biomass in the control and experimental groups (% of dry weight).

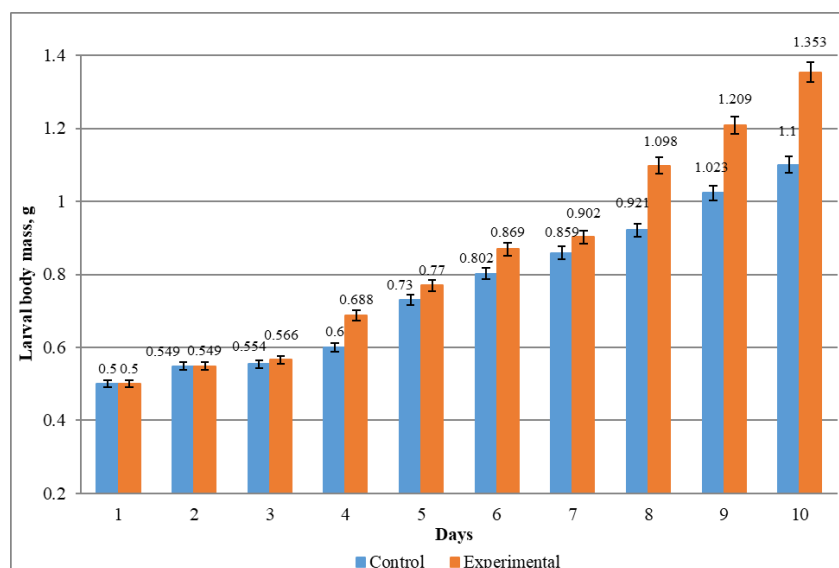


Fig. 7: Growth dynamics of sturgeon larvae in the control and experimental groups during a 10-day rearing period (mean $\pm$ SD, n = 40).

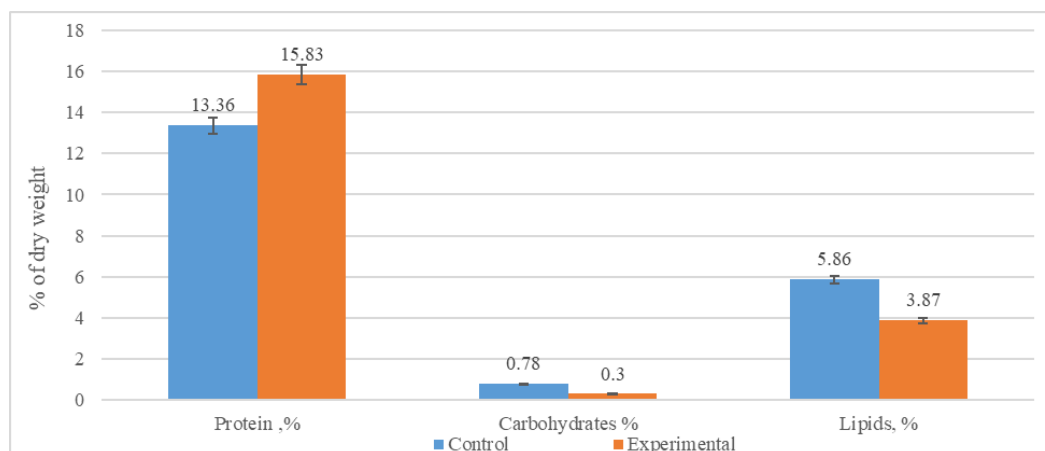


Fig. 8: Comparison of the biochemical composition of muscle tissue in control and experimental sturgeon groups (% of wet weight).

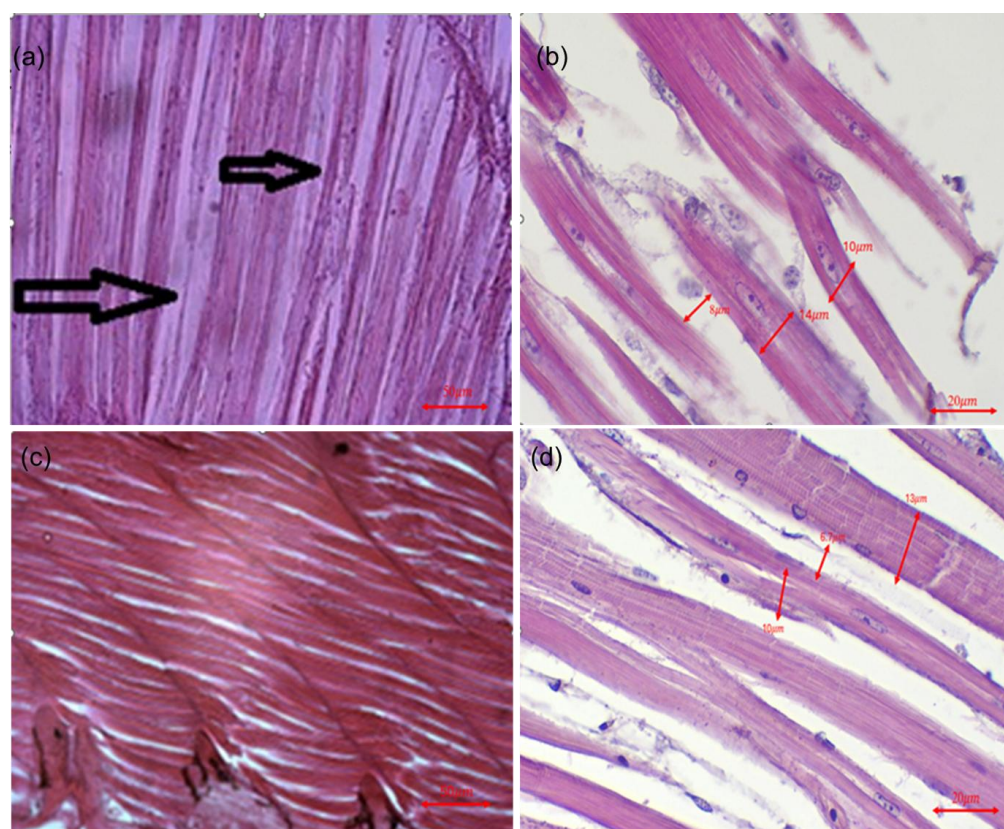


Fig. 9: Microstructure of the muscle tissue in juvenile sturgeon *A. gueldenstaedtii*. (A, B) Control group. A – cavities resulting from sarcoplasmic lysis; magnification: $\times 40$. B – disintegration of muscle fibers (indicated by the arrow); magnification: $\times 60$. Experimental group C – densely packed myofibrils within the muscle fibers; magnification: $\times 40$. D – region showing partial muscle fiber lysis (indicated by the arrow); magnification: $\times 60$.

3.5 Influence on fish muscle morphology

Histological structure of muscle tissue in juvenile Russian sturgeon (*Acipenser gueldenstaedtii*) Fig. 9. Control group showing disrupted muscle fiber organization, sarcolemma damage, and separation of myofibrils (Fig. 9. A, B). Experimental group fed *Artemia* nauplii enriched with *Arthrospira platensis* ZTS-2024, showing well-organized muscle fibers with clear longitudinal striation and peripherally located nuclei (Fig. 9. C, D).

Positive changes in muscle tissue morphology were observed when larvae were fed *Artemia salina* nauplii

enriched with *Arthrospira platensis* ZTS-2024. At the macroscopic level, muscle fibers were compact, with no evident lipid deposits. Microscopic examination demonstrated well-organized and parallel myofibrils with expressed transverse striation and no signs of interstitial lipid accumulation. In addition, relatively large-diameter light fibers were identified, characterized by homogeneous cytoplasm and predominantly peripheral nuclei (Fig. 9 C, D).

The application of live feed enriched with *Arthrospira platensis* ZTS-2024 promoted the formation of dense, functionally mature, and metabolically active muscle tissue in

Russian sturgeon larvae. In the control group, degenerative changes and weak organization of muscle fibers were noted, with fiber diameters ranging from 10 to 13 μm . In contrast, the experimental group exhibited a marked improvement in muscle tissue structural integrity, with fiber diameters reaching 10–14 μm .

These effects may be attributed to the high content of biologically valuable proteins, essential amino acids, and bioactive compounds in *Arthrospira*, which are known to stimulate myogenic processes and support muscle fiber formation and development. Overall, the use of *Arthrospira platensis* ZTS-2024-enriched live feed in aquaculture enhances larval growth performance and muscle tissue quality, enabling the establishment of an environmentally sustainable and circular biotechnological system based on the “aquaculture + microalgae” concept.

4. Conclusion

The success of larval rearing in aquaculture is directly dependent on the availability of high-quality starter feeds. The results show that enrichment of *Artemia parthenogenetica* nauplii with the cyanobacterium *Arthrospira platensis* ZTS-2024 substantially enhances their nutritional value and improves the efficiency of early feeding in sturgeon larvae.

Bioencapsulation with *Arthrospira platensis* ZTS-2024 significantly improved the biochemical composition of *Artemia* nauplii, with increased protein content while lipids and carbohydrates remained within physiologically balanced levels compared with the control group. The high content of proteins, lipids, and carbohydrates in the *A. platensis* ZTS-2024 strain exerted a pronounced positive effect on both linear and weight growth of *Artemia* nauplii. It was further confirmed by biochemical analyses of muscle tissue in juvenile Russian sturgeon (*Acipenser gueldenstaedtii* Brandt, 1833). Larvae fed *Arthrospira*-enriched *Artemia* exhibited higher muscle protein content with lipids maintained at normal levels, indicating more efficient nutrient assimilation and enhanced metabolic activity. Under a constant daily ration, this outcome confirms that growth during early ontogeny is governed primarily by feed quality rather than quantity. Feeding with enriched *Artemia* nauplii during the first week after hatching resulted in an approximately 30% increase in ichthyomass compared with the control group. These findings clearly demonstrate that, during early ontogeny, nutritional quality is a decisive factor governing growth performance and physiological development.

The observed increase in size heterogeneity (coefficient of variation) within the group receiving enriched feed further reflects intensified individual growth rates under conditions of improved nutrition. A key prerequisite for consistent results was the maintenance of controlled environmental and sanitary conditions during *Artemia* cultivation. Specific measures, including population density optimization and the timely removal of cyst debris via flotation, effectively minimized pathogenic risks and improved naupliar viability.

One limitation of the present study is the absence of a comprehensive nutrient profile, particularly detailed analyses of fatty acid composition (DHA, EPA, and ARA) and amino acid profiles, as well as the lack of direct measurements of digestive enzyme activity and immune parameters. Despite these, the consistently positive results obtained across multiple parameters confirm the high nutritional value of *Arthrospira platensis* ZTS-2024 based enrichment. The proposed bioencapsulation strategy represents an environmentally sustainable and economically viable approach for improving larval quality and reducing early mortality in sturgeon aquaculture. Future research should therefore focus on integrated lipidomic and amino acid assessments, evaluation of gastrointestinal physiology and immune responses, and validation of long-term effects under commercial hatchery conditions.

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Conflict of Interest

There are no conflicts to declare.

Supporting Information

Not applicable.

CRedit Statement

All authors contributed to the preparation of the final version of the manuscript and approved its content. **Kenzhegul Bolatkhan:** Conceptualization, Methodology, Investigation, Data curation, Writing – Original draft. **Damys Salauat:** Investigation, Formal analysis, Data curation, Visualization. **Saule M. Shalgimbayeva:** Methodology, Investigation, Validation. **Nurzia R. Akmukhanova:** Formal analysis, Data curation, Visualization. **Bolatkhan K. Zayadan:** Conceptualization, Methodology, Project administration, Supervision, Writing – Review & editing. **Aidana Askar:** Investigation, Data curation. **Mehmet Gökoğlu:** Conceptual guidance, Methodological support, Writing – Review & editing.

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