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Growth Performance of Common Carp (*Cyprinus Carpio*) and Silver Carp (*Hypophthalmichthys Molitrix*) Cultured at High Stocking Density in In-Pond Raceway System (IPRS)

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ABSTRACT: This study evaluated the growth performance of common carp (*Cyprinus carpio*) and silver carp (*Hypophthalmichthys molitrix*) reared at high stocking density in an In-Pond Raceway System (IPRS) over a 120-day production cycle. Fish were fed a commercial floating diet formulated to meet their nutritional requirements under intensive culture conditions. Growth performance was assessed using final body weight, weight gain (WG), specific growth rate (SGR), daily growth rate (DGR), feed conversion ratio (FCR) and survival rate (SR). Water quality was monitored throughout the culture period through regular measurements of temperature, dissolved oxygen, pH and ammonia concentration. The IPRS maintained suitable water quality conditions and supported satisfactory fish growth at high stocking density. Common carp achieved better feed conversion efficiency, whereas silver carp attained greater growth and higher final biomass. Survival remained high in both species, indicating favorable culture conditions throughout the production cycle. The findings support the use of IPRS technology for intensive carp production and provide practical information for improving stocking density, feed utilization and sustainable aquaculture management.

1. INTRODUCTION

Aquaculture is among the fastest-growing food production sectors worldwide and has become an important component of global food security by supplying high-quality animal protein to a rapidly expanding human population [1]. According to the Food and Agriculture Organization (FAO), aquaculture now accounts for more than half of the fish available for human consumption globally, while the production potential of capture fisheries is constrained by biological and environmental limits. Increasing aquaculture productivity through efficient, resource-conscious and environmentally sustainable production systems has consequently become an important research and production priority.

Freshwater aquaculture holds particular importance in Central Asia, including Uzbekistan, where cyprinid fishes such as common carp (*Cyprinus carpio*) and silver carp (*Hypophthalmichthys molitrix*) are among the economically important cultured species [2]. Their widespread use in aquaculture is associated with rapid growth, broad environmental tolerance, efficient utilization of available natural and supplementary food resources, comparatively low production costs and strong consumer demand. These biological and economic characteristics make carp species suitable for semi-intensive and intensive production systems aimed at increasing fish yield without a proportional expansion of land and water requirements [3].

Conventional earthen ponds remain widely used in developing aquaculture industries because of their relatively simple design and comparatively low construction and operational costs. Under increased stocking densities, conventional pond systems may experience substantial fluctuations in dissolved oxygen, accumulation of organic matter and metabolic wastes and inadequate water circulation. Such conditions can adversely affect fish physiological status, feeding activity, nutrient utilization, growth and survival [4]. Declining water quality under high biomass conditions may further increase production risks and reduce the economic efficiency of pond-based aquaculture.

The In-Pond Raceway System (IPRS) has emerged as a production technology that integrates pond-based aquaculture with more controlled fish rearing and water-management practices [5]. In this system, fish are concentrated within raceway units positioned inside a larger pond, while water is continuously circulated through the culture units. Aeration and water movement support oxygen availability and facilitate the transport and collection of metabolic wastes. Concentrating the cultured biomass within raceways can improve feeding management, facilitate fish observation and harvesting, increase the effective carrying capacity of the production unit and improve control of the culture environment. Previous investigations have reported favorable production outcomes from IPRS-based culture, although information concerning its application to carp production under the environmental and climatic conditions of Central Asia remains limited [6].

Several studies have examined the growth and production characteristics of common carp and other carp species under different aquaculture conditions. Direct comparisons between conventional pond culture and IPRS under similar stocking, feeding and management conditions remain relatively limited. Information is particularly scarce concerning the comparative responses of economically important carp species to alternative culture systems in Uzbekistan. Evaluation of growth, feed utilization, survival and water quality within comparable production environments is important for identifying culture practices capable of improving biological performance while maintaining efficient resource use.

The duration of the production cycle is another important consideration in evaluating aquaculture systems. A 120-day culture period provides sufficient time to assess changes in body weight, length, specific growth rate, feed conversion ratio (FCR), survival and water quality under semi-intensive production conditions. Long-term comparative information of this nature remains limited for *C. carpio* and *C. idella* under Central Asian aquaculture conditions. The absence of such information limits the development of scientifically supported production recommendations that account for local environmental conditions, species characteristics and management practices [7-9].

The present study was designed to conduct a comparative assessment of the 120-day growth performance of common carp (*C. carpio*) and grass carp (*C. idella*) under semi-intensive aquaculture conditions. The investigation focused on growth dynamics, feed conversion ratio, survival rate and selected water quality parameters. Comparison of these variables provides an opportunity to assess differences in species performance and their responses to the prevailing culture environment. The findings may support improved species selection, feeding management, production planning and the development of sustainable freshwater aquaculture practices appropriate for Central Asian conditions [10-15].

Fish meat has substantial nutritional importance because it provides highly digestible protein, essential amino acids, polyunsaturated fatty acids, vitamins and important mineral nutrients. Fish proteins contain essential amino acids such as lysine, methionine and threonine, which are required for normal physiological function and tissue development and are generally characterized by high digestibility [16-29]. Fish lipids may contain nutritionally important long-chain omega-3 polyunsaturated fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These fatty acids have recognized physiological functions and are associated with cardiovascular health and other aspects of human health [16-22]. The nutritional value of cultured fish consequently represents an important consideration when evaluating the contribution of aquaculture to food and nutritional security.

Common carp (*C. carpio*) and grass carp (*C. idella*) are important freshwater aquaculture species in Central Asia and are widely utilized in commercial and semi-intensive production systems. Their importance is related to favorable growth characteristics, adaptability to a range of environmental conditions, availability of culture technologies and comparatively low production costs [30-37]. Their capacity to utilize different dietary resources further contributes to their suitability for pond-based production systems.

Despite their established importance in freshwater aquaculture, several aspects of the physiological and productive responses of these species under increased stocking densities and semi-intensive culture conditions remain insufficiently characterized.

Particular attention is required for the interaction between water quality, physiological stress, feed utilization and growth performance. Stress associated with deteriorating water quality, fluctuations in dissolved oxygen, elevated metabolic waste concentrations, temperature variation and increased stocking density may influence fish metabolism, appetite, feed utilization, immune function and growth. Cortisol is widely recognized as an important physiological indicator of stress in fish and changes in cortisol concentration can provide useful information about the physiological response of cultured fish to environmental and management conditions.

The relationship between water quality variables, physiological stress responses, feed efficiency and growth dynamics is especially relevant when comparing conventional ponds with more controlled culture systems such as IPRS. Changes in dissolved oxygen, temperature, pH, ammonia, nitrite and other water quality characteristics may influence fish performance directly or through physiological stress responses. Assessment of these parameters together with growth and FCR can provide a more comprehensive understanding of the biological efficiency of a culture system.

The present research addresses this knowledge gap by evaluating the growth performance, feed conversion ratio, survival and selected water quality characteristics of *C. carpio* and *C. idella* during a 120-day semi-intensive culture period. The study provides comparative information on species-specific performance under the evaluated production conditions and contributes to the development of scientifically based management strategies for freshwater aquaculture in Central Asia. Such information may assist in optimizing species selection, improving feed utilization, maintaining favorable water quality, reducing production-related stress and increasing the biological and economic efficiency of carp-based aquaculture systems.

Common carp (*Cyprinus carpio*) Silver carp (*Hypophthalmichthys molitrix*)



The main objective of this study was to comprehensively evaluate the growth performance, physiological stress responses and biochemical composition of *C. carpio* and *H. molitrix* reared at high stocking densities in an In-Pond Raceway System (IPRS). The study assessed key indicators of fish performance and physiological condition to characterize the biological responses of both species under intensive culture conditions. The findings provide a scientific basis for evaluating the biological efficiency, production potential and sustainability of IPRS technology for high-density carp aquaculture [38-44].

2. MATERIALS AND METHODS

2.1. Study site and experimental design

The present study formed part of a collaborative Türkiye-Uzbekistan research project conducted at the Aquaculture Research Facility of Fergana State Technical University, Fergana, Uzbekistan. The experiment was designed to assess the suitability of an In-Pond Raceway System (IPRS) for intensive freshwater fish production under the environmental conditions of Uzbekistan and to compare its production performance with that of a conventional earthen pond system.

The trial was conducted during the spring production season and continued for six consecutive months, covering the principal grow-out period of the cultured fish. This period was selected because spring in Uzbekistan is characterized by a progressive increase in water temperature and generally favorable conditions for carp growth. The experimental period permitted assessment of both culture systems under environmental conditions relevant to practical carp farming in the region.

Two culture systems were evaluated: (i) a conventional earthen pond and (ii) an In-Pond Raceway System (IPRS). Both systems were operated concurrently at the same research facility and were exposed to comparable environmental conditions. Culture

management was standardized between treatments wherever practical. This experimental arrangement reduced variation arising from differences in location, climate and routine husbandry and provided a basis for assessing the effect of culture system on fish production.

C. carpio and *H. molitrix* were selected as the experimental species because of their economic importance in freshwater aquaculture in Uzbekistan. Fish were maintained at high stocking densities throughout the grow-out period to assess growth and production responses under intensive culture conditions. Evaluation of the two species within the two culture systems provided comparative information on their production performance under the environmental conditions of the study area.

Management procedures were kept consistent between the experimental groups as far as the characteristics of the respective culture systems permitted. Both fish groups received the same commercial diet according to a predetermined feeding schedule. Feeding practices, routine husbandry, health observations and general farm management were standardized between treatments. Water management followed the operational requirements of each production system while maintaining comparable conditions for the fish. These procedures were established to minimize management-related variation and to attribute observed differences in fish performance primarily to the culture system.

Biological and environmental parameters were monitored throughout the six-month experimental period. Fish growth was assessed through periodic measurements of body weight and relevant growth-performance parameters. Water quality measurements were conducted at regular intervals and included water temperature, dissolved oxygen (DO), pH and other relevant physicochemical characteristics. Feed characteristics, with particular attention to dietary crude protein content, were considered in the evaluation of growth performance and feed utilization. Simultaneous assessment of fish growth, feed utilization and water quality provided a comprehensive basis for comparing production performance between the conventional pond and IPRS [45–50].

The experimental workflow is presented in Fig. 1. The figure describes the main stages of the study, from fish stocking and culture-system operation to feeding, water-quality monitoring, periodic growth measurements and final assessment of production performance.

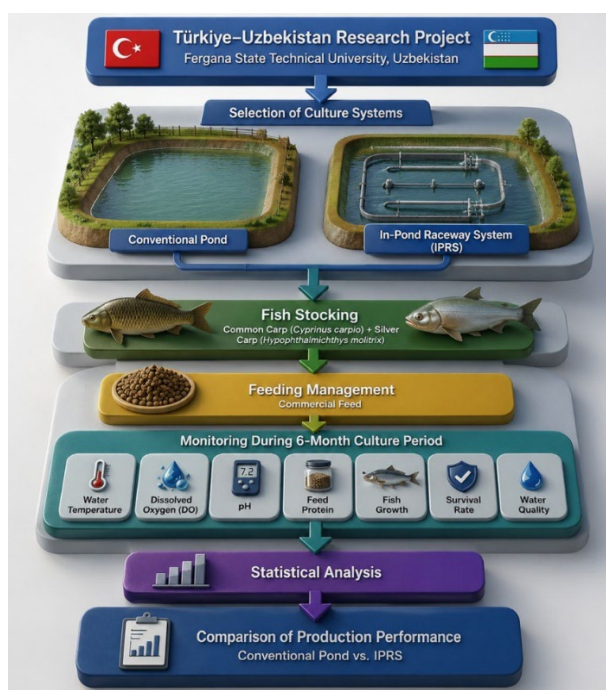


Fig. 1. Experimental design and workflow for comparative culture of common carp (*C. carpio*) and silver carp (*H. molitrix*) in conventional ponds and an In-Pond Raceway System (IPRS).

2.2. Experimental facilities and culture systems

The experiment was conducted using two aquaculture production systems established at the Aquaculture Research Facility of Fergana State Technical University, Uzbekistan: a conventional earthen pond and an In-Pond Raceway System (IPRS). Both systems were operated concurrently throughout the six-month production period under standardized management conditions. The experimental setup was designed to compare the suitability of the two systems for intensive carp production under the environmental conditions of Uzbekistan. The conventional production system consisted of a rectangular earthen pond measuring 12.0 m in length, 6.0 m in width and 2.6 m in depth, with a total water volume of 187.2 m³. Water movement in the pond was maintained through natural circulation and routine pond-management practices used in fish farming. The conventional pond served as the reference system for comparison with the IPRS treatment. The IPRS was installed within a pond of the same dimensions and incorporated a rectangular raceway chamber measuring 12.0 m × 1.2 m. The raceway provided a confined area for high-density fish culture while permitting continuous water exchange with the surrounding pond. The configuration was designed to maintain active water movement and a relatively uniform culture environment within the raceway. Water circulation within the raceway was generated by an air-lift system equipped with perforated PVC diffuser pipes and air-stone diffusers. Fifty-six diffuser units were distributed along the raceway to provide continuous aeration and water movement. Compressed air was supplied by a 1.1-kW blower through PVC pipelines connected to the diffuser network. Fine air bubbles generated within the raceway induced vertical water movement and maintained continuous hydraulic circulation. The circulation system maintained an average water velocity of approximately 0.7 m s⁻¹. This flow rate promoted water mixing, reduced the risk of localized oxygen depletion and facilitated movement of suspended organic particles toward the designated waste-collection area. Continuous hydraulic movement reduced thermal stratification and supported a more homogeneous aquatic environment within the raceway.

Both culture systems received water from the same freshwater source and were managed using the same feeding schedule, feed formulation, routine husbandry procedures and fish-health management protocols. The culture system, represented by the conventional pond and IPRS, was the primary experimental factor evaluated in the study. The schematic configuration of the diffuser-based aeration system, air-lift circulation mechanism and hydraulic flow pattern used in the IPRS is presented in Fig. 2.

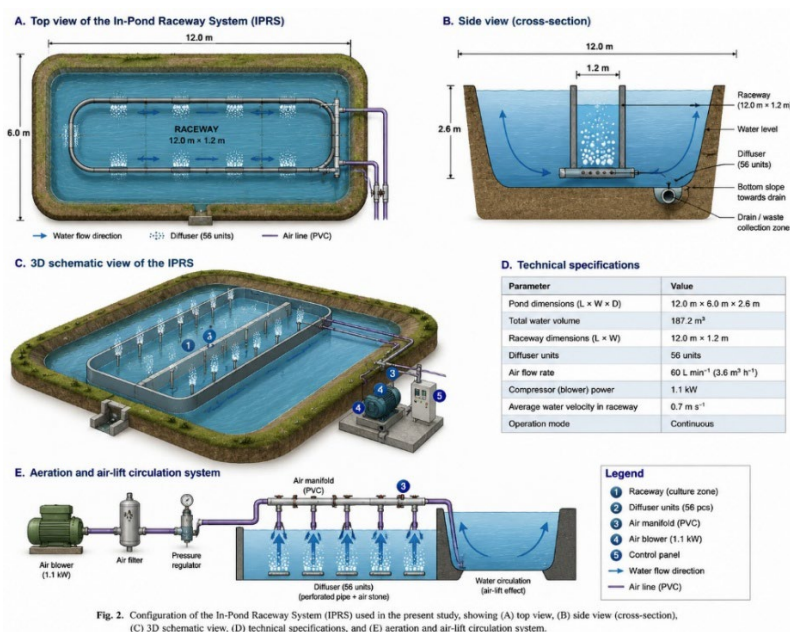


Fig. 2. Configuration of the In-Pond Raceway System (IPRS) used in the present study, showing (A) top view, (B) side view (cross-section), (C) 3D schematic view, (D) technical specifications, and (E) aeration and air-lift circulation system.

Fig. 2. Design and operational configuration of the experimental In-Pond Raceway System (IPRS). (A) Top view of the experimental pond and raceway layout; (B) Cross-sectional view of the raceway and diffuser aeration system; (C) Three-dimensional schematic of the IPRS; (D) Technical specifications of the experimental system; and (E) Air-lift circulation and diffuser aeration mechanism used to maintain continuous water movement and dissolved oxygen distribution throughout the culture period.

2.3. Experimental fish and culture management

Healthy juvenile *C. carpio* and *H. molitrix* were obtained from a certified freshwater hatchery and transported to the Aquaculture Research Facility of Fergana State Technical University. Upon arrival, the fish were visually inspected and individuals exhibiting external lesions, abnormal behavior, or visible signs of disease were excluded from the experiment.

Before stocking, the fish underwent a 10-day acclimation period under experimental facility conditions. During acclimation, continuous aeration was provided and the fish were fed the same commercial diet used during the experimental period. Water quality was maintained within the recommended range for carp culture to reduce transport-related stress and facilitate physiological adaptation to the experimental environment. At the start of the experiment, common carp had a mean initial body weight of $10.0 \pm \text{SD}$ g and a mean total length of $7.0 \pm \text{SD}$ cm, while silver carp had a mean initial body weight of $9.0 \pm \text{SD}$ g and a mean total length of $6.5 \pm \text{SD}$ cm. Fish with relatively uniform body size were randomly selected for stocking to reduce initial size variation among the experimental groups.

A total of 10,000 juvenile fish were stocked in the experimental production system, comprising 6,000 common carp and 4,000 silver carp. The fish were maintained under intensive culture conditions throughout the six-month production period. A commercially manufactured floating feed produced in Tashkent, Uzbekistan, was used throughout the experiment. The diet contained 25% crude protein and was provided once daily. The daily feeding ration was maintained at approximately 10% of total standing fish biomass and was adjusted periodically according to changes in mean fish body weight obtained during routine sampling.

Fish health and behavioral condition were monitored daily throughout the experimental period. Growth measurements were conducted once or twice per week according to fish development and management requirements. During each sampling event, individual body weight and total length were measured using a calibrated digital balance and measuring board. Fish were handled carefully and returned to the culture system immediately after measurement to minimize handling-related stress. Feeding, health monitoring, sampling and routine husbandry procedures were standardized throughout the experimental period. Water quality was maintained within the recommended range for intensive carp culture. Mean water temperature ranged from 18 to 20°C, pH remained between 7.0 and 8.0 and total ammonia concentration remained below 0.8 mg L^{-1} . Continuous aeration and water circulation maintained dissolved oxygen concentrations at levels suitable for intensive fish culture throughout the production cycle.

2.4. Water quality monitoring and growth performance assessment

Water quality was monitored throughout the six-month experimental period to maintain environmental conditions suitable for intensive carp culture and to assess the physicochemical characteristics of the culture systems. Measurements were performed at regular intervals using portable water-quality instruments according to standard aquaculture monitoring procedures. Water temperature, dissolved oxygen (DO), pH, total ammonia nitrogen (TAN) and water transparency were selected as the principal environmental variables because of their relevance to fish metabolism, growth, feed utilization, health and survival.

Water temperature ranged from 18 to 20 °C during the experimental period. Dissolved oxygen concentrations ranged from 5.0 to 7.5 mg L^{-1} , while pH values remained between 7.0 and 8.2. Total ammonia nitrogen (TAN) remained below 0.02 mg L^{-1} throughout the study. Water transparency averaged 81 cm, reflecting the prevailing water clarity and planktonic conditions within the culture systems. Fish growth was assessed through periodic sampling conducted once or twice per week. Fish were randomly collected from the experimental systems and handled carefully to minimize sampling-related stress. Individual body weight and total length were measured using a calibrated digital balance with a precision of ± 0.01 g and a measuring board with a precision of ± 1 mm, respectively. Mean body weight obtained during each sampling period was used to adjust the daily feed ration according to changes in standing biomass.

Growth performance was evaluated using standard aquaculture indices, namely weight gain (WG), specific growth rate (SGR), daily growth rate (DGR), feed conversion ratio (FCR) and survival rate (SR). Weight gain was calculated from the difference between final and initial body weight. Specific growth rate was used to express the relative increase in body weight over the culture period, while daily growth rate represented the average increase in body weight per day. Feed conversion ratio was used to assess feed utilization efficiency and survival rate was calculated from the proportion of fish remaining at the end of the experimental period relative to the initial number stocked. During the experimental period, weight gain ranged from 3.5 to 4.1

g, while mean SGR was $1.55 \pm 0.12\%$ day⁻¹. Mean DGR was 2.8 ± 0.4 g day⁻¹ and FCR averaged 1.95 ± 0.18 . The mean survival rate was $90.5 \pm 2.8\%$. These parameters were used to characterize growth, feed utilization and survival of the cultured fish under the evaluated production conditions.

All biological measurements were conducted by the same research team using standardized sampling and measurement procedures to minimize observer-related variation. The combined assessment of water quality and fish growth provided a basis for evaluating the biological performance and culture conditions of the conventional pond and In-Pond Raceway System (IPRS).

2.5. Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). Quantitative data are expressed as mean $\pm$ standard deviation (SD). Data distribution was assessed using the Shapiro-Wilk test and homogeneity of variances was evaluated with Levene's test before conducting comparative analyses. Differences between the conventional pond and In-Pond Raceway System (IPRS) were assessed using an independent-samples Student's t-test. The analysis included water quality variables and fish production parameters, namely weight gain (WG), specific growth rate (SGR), daily growth rate (DGR), feed conversion ratio (FCR), survival rate (SR) and condition factor (K). When Levene's test indicated unequal variances, the unequal-variance form of the t-test (Welch's correction) was applied. Statistical significance was established at $P < 0.05$. Graphs and summary tables were prepared using Microsoft Excel 2021 (Microsoft Corporation, Redmond, WA, USA).

2.6. Growth performance calculations

Growth performance of *C. carpio* and *H. molitrix* was evaluated using standard aquaculture performance indices. Calculations were based on initial and final body weight measurements recorded during the experimental period and were applied consistently across the experimental treatments.

The following growth and production indices were calculated:

Weight gain (WG, g)

$$WG = W_f - W_i$$

where W_f is the final body weight (g) and W_i is the initial body weight (g).

Specific growth rate (SGR, % day⁻¹)

$$SGR = \frac{\ln W_f - \ln W_i}{t} \times 100$$

where W_f is the final body weight (g), W_i is the initial body weight (g) and t is the culture period (days).

Daily growth rate (DGR, g day⁻¹)

$$DGR = \frac{W_f - W_i}{t}$$

where t is the duration of the experiment (days).

Feed conversion ratio (FCR)

$$FCR = \frac{\text{Feed intake (g)}}{\text{Weight gain (g)}}$$

where feed intake represents the total amount of feed consumed during the experimental period.

Survival rate (SR, %)

$$SR = \frac{N_f}{N_i} \times 100$$

where N_i is the initial number of stocked fish and N_f is the final number of surviving fishes

Condition factor (K)

$$K = \frac{100W}{L^3}$$

where W is body weight (g) and L is total length (cm).

All growth indices were calculated separately for each experimental treatment and were subsequently used for statistical comparison between the conventional pond and the In-Pond Raceway System (IPRS).

2.7. Project framework and ethical considerations

This study was conducted within the framework of the Uzbekistan–Türkiye International Joint Research Project entitled “Implementation of In-Pond Raceway System (IPRS) Technology to Develop the Fisheries Industry of the Republic in Accordance with International Standards and Enhance the Export Potential of Fish Products,” funded under Contract No. AL-9825035903. The project is focused on introducing modern IPRS technology into the aquaculture sector of Uzbekistan, improving production efficiency and strengthening scientific collaboration between Uzbekistan and Türkiye. The present study was conducted in accordance with the approved project work plan and established aquaculture research protocols.

All experimental procedures involving fish followed internationally accepted principles for the care and use of aquatic animals in scientific research. Fish handling, feeding, sampling and routine husbandry were performed by trained personnel using standardized aquaculture procedures. Appropriate measures were taken throughout the experimental period to minimize handling-related stress and maintain fish health and welfare.

2.8. Experimental workflow

The experimental workflow was structured to maintain consistent management practices and reliable data collection throughout the six-month culture period. Before fish stocking, the In-Pond Raceway System (IPRS) and conventional pond were inspected, cleaned and prepared for operation. The aeration and water-circulation systems were tested before stocking to verify proper operation and stable hydraulic conditions. Fish were acclimated for 10 days and randomly distributed into the experimental culture systems after acclimation. Throughout the culture period, fish were fed once daily with a commercial diet containing 25% crude protein at a feeding rate equivalent to 10% of the estimated standing biomass. Water quality parameters, including temperature, dissolved oxygen, pH, total ammonia nitrogen (TAN) and water transparency, were monitored at regular intervals to maintain suitable culture conditions.

Fish growth was evaluated through periodic biometric sampling. Individual body weight and total length were recorded and growth performance indices, including weight gain (WG), specific growth rate (SGR), daily growth rate (DGR), feed conversion ratio (FCR), survival rate (SR) and condition factor (K), were calculated using the specified equations. The collected data were compiled, processed and statistically analyzed to compare the biological and production performance of the conventional pond and IPRS.

3. RESULTS AND DISCUSSION

3.1. Water quality parameters

Water quality remained within acceptable limits for intensive carp culture throughout the six-month experimental period. Continuous aeration and water circulation in the In-Pond Raceway System (IPRS) supported stable environmental conditions and maintained a suitable culture environment for fish growth and survival. Water temperature ranged from 18 to 20 °C during the experimental period. Dissolved oxygen concentrations ranged from 5.0 to 7.5 mg L⁻¹ indicating adequate oxygen availability in both culture systems. The pH remained relatively stable, ranging from 7.0 to 8.2, providing suitable conditions for freshwater fish culture.

The mean concentration of total ammonia nitrogen (TAN) was 0.02 mg L⁻¹ throughout the experimental period, consistent with favourable nitrogen conditions within the culture systems. Water transparency averaged 81 cm, corresponding to relatively clear water and active planktonic development during the culture period. The measured water quality parameters remained within suitable ranges for the culture of *C. carpio* and *H. molitrix* and provided favorable environmental conditions for fish growth, feed utilization and survival. Table-1 presents the mean water quality parameters recorded during the experimental period.

Table 1. Water quality parameters during the experimental period

Parameter	Unit	Recorded value
Water temperature	°C	22-28
Dissolved oxygen	mg L ⁻¹	5.0-7.5
pH	–	7.0-8.2
Total ammonia nitrogen (TAN)	mg L ⁻¹	0.02
Water transparency	cm	81

3.2. Growth performance of fish

The growth performance of fish reared in the conventional pond and In-Pond Raceway System (IPRS) is presented in Table-2. Initial body weight was similar between the two treatments, with a mean value of 10.0 ± 0.3 g and no statistically significant difference was detected at the beginning of the experiment ($p > 0.05$). After the six-month culture period, fish reared in the IPRS attained a significantly higher final body weight of 1350 ± 150 g, compared with 1185 ± 125 g in the conventional pond ($p < 0.05$). Weight gain followed the same pattern, reaching 1340 ± 150 g in the IPRS and 1175 ± 125 g in the conventional pond.

Specific growth rate (SGR) was $2.72 \pm 0.06\%$ day⁻¹ in the IPRS and $2.61 \pm 0.05\%$ day⁻¹ in the conventional pond. Daily growth rate (DGR) was 7.44 ± 0.83 g day⁻¹ and 6.53 ± 0.69 g day⁻¹, respectively. Both SGR and DGR were significantly higher in the IPRS treatment ($p < 0.05$). Feed conversion ratio (FCR) was 1.60 ± 0.12 in the IPRS and 1.89 ± 0.14 in the conventional pond, with a significant difference between the two systems ($p < 0.05$). Survival rate was $97.0 \pm 1.2\%$ in the IPRS and $92.8 \pm 2.1\%$ in the conventional pond ($p < 0.05$). Condition factor (K) was 1.95 ± 0.11 in the IPRS and 1.82 ± 0.08 in the conventional pond. The difference was not statistically significant ($p > 0.05$). The growth, feed utilization and survival data indicate better production performance in the IPRS treatment during the experimental period.

Table 2 Comparison of growth performance of fish cultured in the conventional pond and the In-Pond Raceway System (IPRS)*

Parameter	Unit	Conventional pond	IPRS	P-value
Initial body weight	g	10.0 ± 0.3	10.0 ± 0.3	NS
Final body weight	g	1185 ± 125	1350 ± 150	<0.05
Weight gain (WG)	g	1175 ± 125	1340 ± 150	<0.05
Specific growth rate (SGR)	% day ⁻¹	2.61 ± 0.05	2.72 ± 0.06	<0.05
Daily growth rate (DGR)	g day ⁻¹	6.53 ± 0.69	7.44 ± 0.83	<0.05
Feed conversion ratio (FCR)	–	1.89 ± 0.14	1.60 ± 0.12	<0.05
Survival rate (SR)	%	92.8 ± 2.1	97.0 ± 1.2	<0.05
Condition factor (K)	–	1.82 ± 0.08	1.95 ± 0.11	>0.05

*Values are presented as mean $\pm$ standard deviation (SD). WG, weight gain; SGR, specific growth rate; DGR, daily growth rate; FCR, feed conversion ratio; SR, survival rate; K, condition factor. NS: not significant ($p > 0.05$).

3.3. Production performance and culture efficiency

Fish reared in the IPRS had higher production values than fish maintained in the conventional pond during the six-month experimental period (Table-3). The IPRS treatment recorded greater final body weight, weight gain, specific growth rate (SGR), daily growth rate (DGR), feed utilization efficiency and survival rate. The differences in several production parameters were

statistically significant, whereas condition factor (K) did not differ significantly between the two systems. Final body weight reached 1350 ± 150 g in the IPRS and 1185 ± 125 g in the conventional pond. Weight gain was 1340 ± 150 g and 1175 ± 125 g, respectively. The higher body weight and weight gain recorded in the IPRS were associated with the continuous movement of water through the raceway and the associated culture conditions maintained during the experimental period. The IPRS provided a confined culture area with active water circulation, which may have supported more consistent environmental conditions for fish growth.

Specific growth rate (SGR) and daily growth rate (DGR) were significantly higher in the IPRS than in the conventional pond ($p < 0.05$). Fish reared in the IPRS achieved an SGR of $2.72 \pm 0.06\%$ day⁻¹ and a DGR of 7.44 ± 0.83 g day⁻¹, compared with $2.61 \pm 0.05\%$ day⁻¹ and 6.53 ± 0.69 g day⁻¹, respectively, in the conventional pond. The higher growth rates observed in the IPRS may be associated with the continuous water movement, adequate dissolved oxygen availability and removal of suspended wastes from the raceway. Feed conversion ratio (FCR) was significantly lower in the IPRS (1.60 ± 0.12) than in the conventional pond (1.89 ± 0.14 , $p < 0.05$). The lower FCR represents a smaller quantity of feed required per unit of weight gain and indicates better feed utilization in the IPRS treatment. Improved feed conversion has direct relevance to production economics because feed constitutes a major operating cost in intensive aquaculture. Efficient feed utilization may further reduce the quantity of feed-derived organic matter entering the culture environment.

Survival rate was $97.0 \pm 1.2\%$ in the IPRS and $92.8 \pm 2.1\%$ in the conventional pond, with a significant difference between the systems ($p < 0.05$). The higher survival recorded in the IPRS was associated with the continuous aeration and water circulation maintained within the raceway. Stable dissolved oxygen concentrations and regular movement of water may have reduced unfavorable environmental conditions during the culture period. Condition factor (K) was 1.95 ± 0.11 in the IPRS and 1.82 ± 0.08 in the conventional pond. The difference was not statistically significant ($p > 0.05$). The similar K values indicate that the two culture systems maintained comparable body condition despite the differences observed in growth, feed conversion and survival.

Table-3 shows higher growth and feed-use performance in the IPRS compared with the conventional pond. The differences in final body weight, weight gain, SGR, DGR, FCR and survival support the suitability of the IPRS for intensive carp culture under the conditions evaluated in this study. The results provide a basis for further assessment of IPRS technology as a production system for improving fish yield and feed-use efficiency under the environmental conditions of Uzbekistan.

Table 3. Production performance and culture efficiency

Parameter	Conventional pond	IPRS	Improvement (%)
Final body weight (g)	1185 ± 125	1350 ± 150	13.9
Weight gain (g)	1175 ± 125	1340 ± 150	14.0
Specific growth rate (% day ⁻¹)	2.61 ± 0.05	2.72 ± 0.06	4.2
Daily growth rate (g day ⁻¹)	6.53 ± 0.69	7.44 ± 0.83	13.9
Feed conversion ratio	1.89 ± 0.14	1.60 ± 0.12	-15.3
Survival rate (%)	92.8 ± 2.1	97.0 ± 1.2	4.5

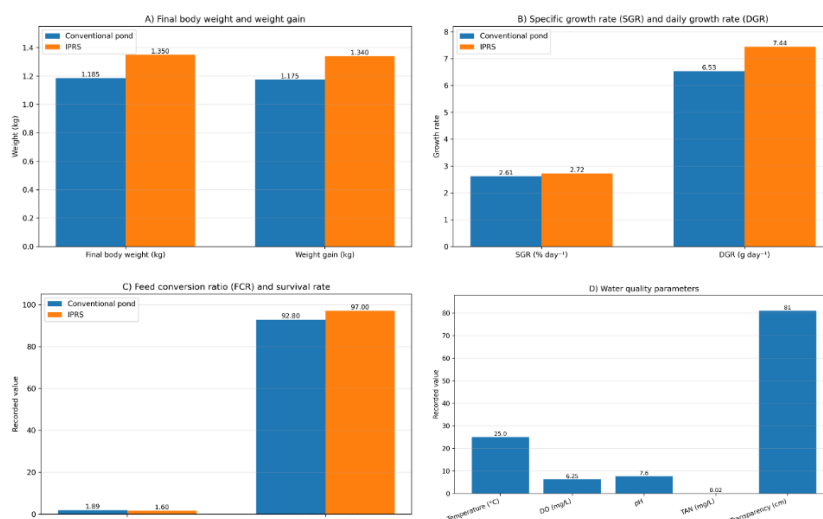


Fig. 3. Growth performance, feed utilization, survival rate and water quality parameters of fish cultured in the conventional pond and IPRS: (A) final body weight and weight gain; (B) specific growth rate and daily growth rate; (C) feed conversion ratio and survival rate; and (D) water quality parameters.

3.4. Relative improvement of production indicators in the IPRS

The relative performance of the IPRS and conventional pond was assessed using the principal growth, feed utilization and survival parameters presented in Table 3 and Fig. 3A-D. The IPRS treatment recorded higher values for the major production parameters, although the magnitude of difference varied among the measured indicators. Final body weight increased from 1185 g in the conventional pond to 1350 g in the IPRS, representing an increase of approximately 13.9%. Weight gain followed a similar pattern, increasing from 1175 g to 1340 g, equivalent to an increase of approximately 14.0%. The higher values recorded in the IPRS may be related to the continuous water movement and oxygen distribution maintained within the raceway during the culture period.

Specific growth rate (SGR) increased from 2.61% day⁻¹ in the conventional pond to 2.72% day⁻¹ in the IPRS, corresponding to an increase of approximately 4.2%. Although the difference in SGR was relatively small in numerical terms, its effect accumulated throughout the six-month culture period and was accompanied by a higher final body weight in the IPRS treatment. Daily growth rate increased from 6.53 to 7.44 g day⁻¹, representing an increase of approximately 13.9%.

Feed conversion ratio (FCR) decreased from 1.89 in the conventional pond to 1.60 in the IPRS. Since lower FCR values represent greater feed-use efficiency, the observed reduction corresponds to an improvement of approximately 15.3% in feed conversion. The difference may be associated with conditions within the raceway that support feed access and utilization, together with continuous water movement and waste transport. Survival rate increased from 92.8% in the conventional pond to 97.0% in the IPRS, corresponding to a relative increase of approximately 4.5%. The higher survival recorded in the IPRS occurred under continuous aeration and water circulation, which maintained suitable dissolved oxygen conditions during the culture period. The observed survival pattern supports the suitability of the IPRS environment for maintaining fish at the stocking density used in the experiment.

Table 4. Relative changes in growth and production indicators of fish cultured in the IPRS compared with the conventional pond system

Parameter	Conventional pond	IPRS	Relative change (%)*
Final body weight (g)	1185	1350	13.9
Weight gain (g)	1175	1340	14.0
Specific growth rate (% day ⁻¹)	2.61	2.72	4.2

Daily growth rate (g day ⁻¹)	6.53	7.44	13.9
Feed conversion ratio	1.89	1.60	-15.3
Survival rate (%)	92.8	97.0	4.5
Condition factor	1.82	1.95	7.1

*Positive values indicate an increase in the IPRS, whereas the negative value for FCR indicates improved feed efficiency because lower FCR values are desirable.

The condition factor (K) differed only slightly between the two culture systems, with values of 1.82 in the conventional pond and 1.95 in the IPRS. The difference was not statistically significant ($p > 0.05$), indicating comparable body condition between the two treatments. The higher numerical value recorded in the IPRS should be interpreted cautiously because the difference did not reach statistical significance.

The IPRS treatment recorded higher final body weight, weight gain, daily growth rate and survival, together with a lower feed conversion ratio than the conventional pond. Among the measured parameters, the largest relative difference was observed for feed conversion ratio, followed by weight gain and daily growth rate. The observed pattern suggests that the IPRS supported greater biomass gain with more efficient feed utilization and lower fish mortality during the culture period.

3.5. Performance of the In-Pond Raceway System (IPRS)

The performance of the IPRS was assessed using water quality, growth, feed utilization, survival and production parameters measured during the six-month culture period. The IPRS treatment recorded higher values for the main growth and production indicators than the conventional pond system. Water quality remained within suitable ranges in both culture systems. The IPRS incorporated continuous water circulation and mechanical aeration, which maintained regular water movement and adequate dissolved oxygen availability within the raceway. These operating conditions provided a controlled environment for fish culture during the experimental period.

Fish reared in the IPRS attained higher final body weight, weight gain and daily growth rate than fish maintained in the conventional pond. The lower feed conversion ratio recorded in the IPRS indicates more efficient feed utilization. Feed-use efficiency is an important production parameter in intensive aquaculture because feed accounts for a substantial proportion of operating expenditure. Survival rate was higher in the IPRS than in the conventional pond. The IPRS maintained continuous water circulation through the culture area, while suspended material and metabolic wastes were transported away from the main fish-holding zone. The combination of aeration and water movement provided stable culture conditions during the experimental period.

The raceway configuration permits high-density fish culture within a defined section of an existing pond. The surrounding pond water serves as the source and receiving environment for the raceway circulation system, while the larger pond area can support sedimentation and biological processing of nutrients and suspended materials. This configuration may allow greater use of existing pond infrastructure without requiring an equivalent increase in pond area. The growth, feed utilization, survival and production data obtained in this study support the use of IPRS technology for intensive freshwater fish culture under the environmental conditions of Uzbekistan. The higher biomass gains and lower FCR recorded in the IPRS treatment are relevant to production efficiency, while the higher survival rate provides an additional advantage for maintaining harvestable biomass during the culture period.

Figure 4 presents the relative production performance of fish cultured in the conventional pond and IPRS. To allow comparison among parameters expressed in different units, the values obtained for the conventional pond were standardized to 100% and the corresponding IPRS values were expressed as percentages relative to the conventional pond. The IPRS values were higher for the principal growth parameters. Final body weight reached 113.9%, while weight gain reached 114.0% relative to the conventional pond. Daily growth rate was 113.9% of the conventional pond value. These relative values correspond to greater biomass accumulation and faster daily growth in fish reared under IPRS conditions during the six-month culture period.

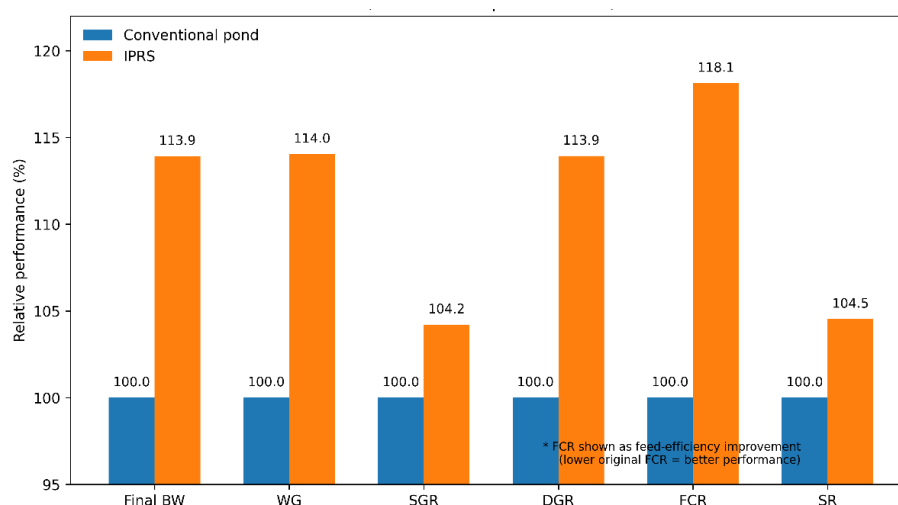


Fig. 4. Comparative production performance between the conventional pond and the In-Pond Raceway System

The specific growth rate (SGR) increased to 104.2% relative to the conventional pond. Although the relative difference was smaller than that observed for final body weight and weight gain, the higher SGR was maintained throughout the production cycle and was associated with greater final harvest weight. The survival rate reached 104.5% relative to the conventional pond, corresponding to an increase from 92.8% to 97.0%. The higher survival recorded in the IPRS treatment occurred under continuous aeration and water circulation, which maintained suitable culture conditions during the experiment.

Figure 5 presents the relative performance of the two culture systems. The IPRS treatment recorded higher values for growth, feed utilization and survival than the conventional pond. The combined pattern of these production indicators supports the application of IPRS technology for intensive freshwater fish culture under the environmental conditions evaluated in Uzbekistan.

3.6. Implications of the In-Pond Raceway System for sustainable aquaculture production

The findings of this study indicate that the IPRS can improve several biological and production parameters of freshwater fish culture under the environmental conditions evaluated in Uzbekistan. Fish reared in the IPRS attained greater final body weight and weight gain, higher growth rates and survival and a lower feed conversion ratio than fish maintained in the conventional pond. The combined response of these parameters reflects improved production performance under the IPRS conditions.

A major feature of the IPRS is the use of continuous water circulation and mechanical aeration within a confined culture area. The system maintained regular water movement and suitable dissolved oxygen concentrations during the experimental period. Continuous hydraulic movement may facilitate the transport of suspended materials away from the fish-holding area and reduce the formation of localized zones with unfavorable water quality. Such conditions are relevant to maintaining fish growth and survival at high stocking densities.

Feed conversion ratio was lower in the IPRS than in the conventional pond, indicating more efficient use of the commercial diet. Feed is a major component of operating expenditure in intensive aquaculture, making feed conversion an important parameter for production assessment. Improved feed utilization may reduce the quantity of feed required for a given increase in fish biomass and may limit the amount of feed-derived organic material entering the culture environment.

Survival was higher in the IPRS treatment, reaching $97.0 \pm 1.2\%$, compared with $92.8 \pm 2.1\%$ in the conventional pond. The higher survival occurred under continuous aeration and water circulation, with dissolved oxygen maintained between 5.0 and 7.5 mg L⁻¹ during the experimental period. These conditions may have contributed to lower environmental stress and improved retention of harvestable biomass. The IPRS configuration can be incorporated into an existing earthen pond by allocating a defined area for the raceway while retaining the surrounding pond as part of the water-circulation system. This arrangement provides an opportunity to increase fish stocking and production within existing pond infrastructure without requiring an equivalent expansion of pond area. The practical value of this approach is particularly relevant to farms where land and water resources limit expansion of conventional pond production.

The present results support the use of IPRS technology as a potential approach for intensifying freshwater aquaculture under the environmental conditions of Uzbekistan. The higher growth performance, improved feed conversion and greater survival recorded in the IPRS treatment provide a basis for further evaluation of the technology at commercial scale. Long-term studies should assess production economics, water and energy requirements, nutrient discharge, carrying capacity and performance across different seasons before wider implementation.

The six-month experiment revealed clear differences in production performance between the IPRS and conventional pond systems. Water quality remained within suitable ranges for carp culture in both treatments, while the IPRS maintained continuous water circulation and mechanical aeration within the raceway. Fish cultured in the IPRS attained a final body weight of 1350 ± 150 g, compared with 1185 ± 125 g in the conventional pond. Weight gain was 1340 ± 150 g and 1175 ± 125 g, respectively. Specific growth rate was $2.72 \pm 0.06\%$ day⁻¹ in the IPRS and $2.61 \pm 0.05\%$ day⁻¹ in the conventional pond, while daily growth rate reached 7.44 ± 0.83 and 6.53 ± 0.69 g day⁻¹, respectively. The IPRS had a lower feed conversion ratio (1.60 ± 0.12) than the conventional pond (1.89 ± 0.14), with a significant difference between treatments ($p < 0.05$).

Survival rate was $97.0 \pm 1.2\%$ in the IPRS and $92.8 \pm 2.1\%$ in the conventional pond. Condition factor was 1.95 ± 0.11 and 1.82 ± 0.08 , respectively, with no significant difference between treatments ($p > 0.05$). The higher growth, feed-use efficiency, and survival recorded in the IPRS treatment resulted in greater production performance during the experimental period. The conceptual framework presented in Figure 6 links the main operating features of the IPRS with the biological responses observed in the experiment. Continuous water circulation, mechanical aeration, and movement of suspended wastes formed the principal system characteristics evaluated in relation to fish growth, feed utilization, and survival. The findings support IPRS as a suitable system for intensive freshwater fish culture under the conditions examined in Uzbekistan. The technology offers a means of increasing fish production within existing pond infrastructure while maintaining controlled water movement and aeration. Assessment of economic return, resource consumption, environmental load, and seasonal performance will be required to establish the long-term feasibility of IPRS adoption in commercial aquaculture.

4. CONCLUSION

The present study established that the In-Pond Raceway System (IPRS) improved the production performance of cultured fish compared with the conventional pond system under the environmental conditions of Uzbekistan. Fish reared in the IPRS attained higher final body weight, weight gain, specific growth rate, daily growth rate, and survival, together with a lower feed conversion ratio. These results indicate that the raceway configuration provided suitable conditions for intensive fish culture during the six-month production period. The IPRS maintained continuous water circulation and mechanical aeration, supporting stable dissolved oxygen conditions and regular movement of water through the culture area. These operating characteristics are relevant to high-density fish culture because they facilitate water exchange and the movement of suspended wastes away from the main fish-holding area. The lower FCR recorded in the IPRS treatment reflects improved feed-use efficiency, while the higher survival rate contributed to greater retention of harvestable biomass. The results obtained in this study support the application of IPRS technology for intensifying freshwater aquaculture within existing pond infrastructure. The system provides an opportunity to increase fish production without requiring a proportional expansion of pond area. Its suitability for sustainable aquaculture in Uzbekistan is supported by the combination of improved growth, feed utilization, and survival observed during the experimental period. The study was conducted during a single production cycle under a specific set of environmental and management conditions. Further research should examine seasonal variation, stocking density, feeding strategies, species combinations, energy consumption, production economics, and environmental loads. Multi-cycle and commercial-scale trials will be important for determining the long-term technical and economic feasibility of IPRS technology under Central Asian aquaculture conditions. Based on the measured production responses, IPRS represents a viable approach for intensive freshwater fish production under the conditions evaluated in Uzbekistan. The technology has potential to improve biomass production and feed-use efficiency while making greater use of existing pond infrastructure. Continued evaluation at different production scales and environmental conditions will provide a stronger basis for its wider adoption in sustainable aquaculture systems.

CREDIT AUTHOR CONTRIBUTION STATEMENT

In this study, the authors contributed in the following roles:

- a) Mamatkulov M.X. – Conceptualization of the study, development of the experimental design and preparation of the final analysis and conclusions.
- b) Dekhkanov Z.K. – Execution of experimental work in the aquaculture system, fish husbandry and monitoring of growth performance parameters.
- c) Sotvoldiyev A.M. – Laboratory analyses, including measurement of water quality parameters (pH, dissolved oxygen, temperature) and statistical data processing.
- d) Khamdamova Sh.Sh. – Supervision of the research process, coordination of all experimental stages as scientific advisor and contribution to manuscript review and editing.
- e) Khamrakulova M. – Calculation of feed conversion ratio (FCR), growth performance indicators, biomass estimation and preparation of statistical analysis and graphical materials.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DECLARATION ON THE USE OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN WRITING

During the preparation of this manuscript, ai-based writing assistance tools were used in a limited capacity solely for language editing and improvement of linguistic quality. All scientific results, analyses and conclusions were independently developed by the authors, who retain full responsibility for the integrity and final content of the manuscript.

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DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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