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Technological approaches to grow-out: a comparative study of pikeperch (*Sander lucioperca*) culture in three different production systems during the growing season

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This study compares pikeperch (*Sander lucioperca*) production in three systems: a recirculating aquaculture system (RAS), an in-pond raceway system (IPRS), and a traditional pond polyculture (POND). Each system was stocked with 1500 juveniles and cultured for 24 weeks. The RAS fish exhibited the most intensive growth, achieving the highest final total length, final body weight, condition factor and specific growth rate, alongside the lowest food conversion ratio (FCR). However, the increased hepatosomatic index, intraperitoneal fat and ammonia levels suggested an increased metabolism. Notably, RAS fish displayed the highest frequency of fin erosion, particularly in the caudal and first and second dorsal fins. The IPRS group exhibited slower growth, higher FCR and higher plasma glucose levels than the other groups. IPRS fish also showed fin erosion in caudal and both pectoral fins. RAS and IPRS fish demonstrated similar survival rates. Conversely, the POND group exhibited significantly lower survival, likely because of adaptability and water quality issues. Blood plasma analysis of POND fish indicated starvation, marked by elevated alanine aminotransferase and lipase levels, supported by non-existing fat reserves. In summary, RAS yielded the best growth and feed efficiency, although it was associated with increased metabolic stress and fin erosion. IPRS showed slower growth but proved cost-effective during the growing season. Traditional pond culture was unsuccessful owing to adaptability in and the water quality of ponds. An economic evaluation revealed that production costs per pikeperch juvenile were significantly lower in the IPRS compared with that in the RAS, thereby compensating for slower growth.

KEYWORDS
pikeperch, production, intensification, rearing technology, physiological status, mortality

1 Introduction

European inland aquaculture has chosen diversification as a tool to increase production (Baekelandt et al., 2018). Pikeperch was selected among other species for intensive aquaculture (Policar et al., 2019) given its high value, rapid growth and good flesh quality. Owing to these traits, pikeperch production in aquaculture is constantly increasing. Conversely, production from open waters has gradually decreased over the years, dropping to ~50% since 1950 (FAO, 2022). This creates an opportunity for farmers to further increase their production to fill the market gap. In Western Europe, such as Belgium and France, insufficient pond farming area forces farmers to produce pikeperch in closed aquaculture systems (RAS). Thereafter, controlled pikeperch aquaculture was highly industrialised, which led to high costs of initial investment and maintenance (Overton et al., 2015). Numerous studies have focused on the optimisation of broodstock management (Malinovskyi et al., 2018, 2019), reproduction (Samarin et al., 2016; Kristan et al., 2018), juvenile and on-growing feeding (Kowalska et al., 2015; Pěnka et al., 2023; Schulz et al., 2007), light regimes (Luchiari et al., 2006), stocking densities (Ljubobratović et al., 2016; Kozłowski and Piotrowska, 2023), biculture stockings (Pěnka et al., 2021, 2024) and use of live feed for larval culture (Imentai et al., 2019; Yanes-Roca et al., 2018; 2020) to further ensure the feasibility of RAS operation. In recent years, a drastic rise in energy costs has decreased the profitability of pikeperch intensive farms, prompting the need for less energy demanding production methods. Extensive or semi-intensive pond culture remains the least expensive option for fish production, but the seasonal nature of fish supply, low species diversity and increasing temperatures, which cause algae blooms and oxygen deficiencies, make pond culture unpredictable and less efficient. Nevertheless, in CEER countries (Central East European countries—Czech Republic, Poland, Hungary, Austria, Slovakia and Germany), the majority of farmed pikeperch (FAO, 2022), as well as the overall share of aquaculture production of up to 80%–88% (Vavrečka et al., 2019), originates from ponds. The existing pond infrastructure in the combination with new technological equipment provides an opportunity to increase the production capacity of ponds. One of the production possibilities were the cages that were used for controlled fish production in Central Europe during the 20th century were partially successful. However, cages have the disadvantages of insufficient water circulation, which is directly related to decreased water quality and low oxygen levels (Brune et al., 2003). The in-pond raceway system (IPRS) provides better water quality, is easy to install in existing ponds and provides better water circulation and aeration while using an air lift as a power medium (Masser, 2012). IPRS has been used in only two published studies on pikeperch culture regarding broodstock management (Ljubobratović et al., 2019) and the grow-out phase of juveniles (Nagy et al., 2022). The study by Nagy et al. (2022) suggests that pikeperch rearing is compatible with IPRS and should be further examined and economically evaluated. Herein, the advantages and disadvantages of traditional fish farming in ponds, modern fish farming using RAS and the hybrid system of IPRS, which combines both approaches to fish culture, are evaluated.

2 Materials and methods

2.1 Place and duration of the experiment

The experiment was conducted in the large scale-experimental RAS and IPRS at the Laboratory of Intensive Aquaculture, Faculty of Fisheries and Protection of Waters, University of South Bohemia in České Budějovice, Czechia and in three experimental ponds belonging to the Experimental Fish Culture Facility of the same faculty as the previous production systems. The duration of the experiment was 168 days (24 weeks) during the growing season, starting on April 11th and finishing on September 26th.

2.2 Production systems

2.2.1 RAS

For this study, a semi-experimental RAS comprising 10 cylindrical tanks, each with a volume of 1.5 m^3, was used (Figure 1). The bottom outflow of the tank was connected directly to a drum mechanical filter 1-FB (IN-EKO Team, Tišnov, Czech Republic) with a flow rate of 28–000 L.h^{-1} and to a moving bed biofiltration unit with a volume of 14.6 m^3 powered by two air-pumps (Secoh El-S-250; 250 L.min^{-1}, Secoh Ltd., Shanghai). After the sterilisation process using an ozone generator OT 10 model (Ozontech s.r.o., Zlín, Czech Republic) with the dose of 10 g per hour and 6 hour application (Kolářová et al., 2021) and saturation with pure oxygen, water was run from the distribution tank gravitationally back into the rearing tanks. The water flow in the tanks was set at an exchange rate of twice per hour for consistent oxygen saturation and efficient faeces discard.

2.2.2 IPRS

The IPRS comprised nine separate floating plastic tanks (Figure 2). Each tank had a volume of 7.2 m^3 (4 × 1.5 × 1.2 m) and was fitted with two stainless steel grated openings on opposite sides. The first grated openingwas located directly under the water surface and provided top inflow. The second grated opening was located at the bottom and enabled the disposal of uneaten feed, faeces and other debris from the tanks into the pond. The water inflow was provided by an airlift located in the siphon under the inlet opening. The airlift through the siphon produced large bubbles of air, creating a slow water current that carried water to the surface. This current provided continuous water exchange inside the rearing tanks while also bringing fresh oxygen-rich water. The IPRS was powered by an air-pump Kubíček 3D19S-051E (940 L.min^{-1}, Kubíček VHS s.r.o., Czech Republic). The open top of the tanks was covered with a net to protect the fish from predators and falling debris. The pond used for this floating system had a total area of 0.3 hectare with an average depth of 1.8 m and was filled by a water from the Blanice River.

FIGURE 1
Large-scale experimental RAS of LIA FFPW USB in Vodňany (V. Kučera).

FIGURE 2
IPRS of LIA, FFPW USB Vodňany consisting of 9 tanks, 7.2m^3 each (V. Kučera).

2.2.3 POND

In this experiment, three identical experimental ponds were used by the POND group. Each pond had a total area of 0.1 ha with an average depth of 1 m (Figure 3). The ponds were filled by the same water channel from the Blanice River as the pond where IPRS was situated. The bottom inflow was fitted with a fine mesh bag to prevent fish from the river from entering the pond. The outflow was fitted with fine bars to prevent the fish from escaping from the pond.

2.3 Experimental groups and feeding

In each rearing system (RAS, IPRS and POND), pikeperch juveniles with a mean initial body weight (IBW) of 51.6 ± 10.33 g were stocked. Each rearing system was stocked in triplicate with 500 individuals per repetition (a total of 1500 juveniles per group, 4500 juveniles in total). Pikeperch was stocked into each rearing system 2 weeks before the start of the experiment to ensure the fish adapted to the new environment. All juvenile pikeperch originated from a RAS–POND combination production system, according to Policar et al. (2016). These juveniles were initially fed floating feed, Skretting Europa-15F (55% protein, 16% fat, 10% fibre, 0.7% ash, 1.5% phosphorus, 19.4 MJ.kg^{-1} digestible energy, size 2–3 mm), which was subsequently provided to the fish during the IPRS and RAS trials. Feed was distributed into the RAS and IPRS tanks using belt feeders for >8 h per day. Depending on the water temperature, oxygen levels and appetite of the fish, the daily feeding ratio (DFR) oscillated from 0.3% to 1.5% of biomass per day. The mean initial

FIGURE 3
Experimental ponds with acreage of 0.1 ha and average depth of 1m in Experimental Fish Culture Facility of FFPW USB Vodňany (photo by V. Kučera).

biomasses were established as follows: 17.2 kg.m^{-1} (RAS) and 3.58 kg.m^{-3} (IPRS), depending on the culture intensity level. Both systems operated under a stock monoculture regime. In POND conditions, 258 kg.ha^{-1} of pikeperch were stocked. To help imitate the conditions of extensive pond culture in Central Europe, the following fish species were added to the polyculture in the following biomasses: common carp (*Cyprinus carpio*), 168 kg.ha^{-1} (177 individuals, IBW 94.3 ± 0.1 g); broodstock of tench (*Tinca tinca*), 74.5 kg.ha^{-1} (8 individuals, IBW 896.5 ± 27.4 g) and broodstock of rudd (*Scardinius erythropthalamus*), 101.5 kg.ha^{-1} (60 individuals, IBW 171.1 ± 0.9 g). The broodstock of tench and rudd was added to provide prey fish for pikeperch via natural spawning.

2.4 Abiotic conditions

In the RAS and IPRS environments, water temperature and oxygen levels were measured daily at 7:00 using a YSI ProODO oximeter (YSI Inc., Yellow Springs, OH, USA). The pH was measured once a day at 7:00 am using a WTW 3310 pH-metre (WTW, Prague, Czech Republic). Total ammonia and nitrite levels were determined daily at 7:30 am using simple titration and colourimetry reference kits, according to Pěnka et al. (2021). All the previously mentioned abiotic conditions in the ponds were measured thrice a week using the same equipment, and sampling was performed at the same time as in the RAS and IPRS. All water quality parameters in each production system are summarised in Table 1.

2.5 Evaluated production parameters

At the beginning of the experiment, 100 individuals were subjected to biometric measurements (body weight [BW], total length [TL] and standard length [SL]) using a measuring board and digital scale (KERN KB 2400-2N; Kern & Sohn, GmbH, Germany). Fin erosion was determined in 90 individuals, following Policar et al. (2016). Before manipulation, fish were anaesthetised using clove oil (0.04 ml. l^{-1}) (Kristan et al., 2014). Blood was collected from 12 individuals from the *vena caudalis* using a heparinised needle (5000 IU/ml, Leciva, Prague, Czech Republic) and a syringe. After plasma centrifugal separation, the samples were stored at −80°C until biochemical analysis. The following biochemical parameters in blood plasma were analysed: total protein (TP), albumin (ALB), globulin (GLB), amylase (AMYL), lipase (LIPA), total cholesterol (TCHOL), glucose (GLU), ammonia (NH_3), triglyceride (TAG), alanine aminotransferase (ALP) and aspartate aminotransferase (AST). The measurement was made using the biochemical analyser FUJI DRI-CHEM NX 500i (FUJIFILM Europe GmbH, Dusseldorf, Germany). After blood sampling, fish were euthanised and dissected to determine the weight of individual internal organs for the calculation of somatic indices such as hepatosomatic index (HSI), intraperitoneal fat index (IPFI), spleensomatic index (SSI), gonadosomatic index (GSI) and relative gut length (RGL). Dissections were performed under veterinary guidance, supported by good practice. During the experiment, the mortality of the cultured fish was checked daily, and all deceased individuals were counted and recorded to calculate the survival rate (SR). For the exact calculation of the feed conversion ratio (FCR), uneaten feed was checked daily during the feeding of the fish and maintenance of the rearing tanks.

TABLE 1 Abiotic conditions in all production systems during the experiment.

Parameter	RAS	IPRS	POND
O_2 (%)	131 ± 14.5	92.1 ± 16.6	90.5 ± 27.9
NO_2^- (mg. L^{-1})	0.67 ± 0.31	0.26 ± 0.14	0.35 ± 0.10
NH_4^+ (mg. L^{-1})	0.68 ± 0.30	0.53 ± 0.28	0.42 ± 0.11
pH	6.86 ± 0.21	7.16 ± 0.26	7.89 ± 0.92
T (°C)	21.9 ± 2.64	17.0 ± 4.07	18.4 ± 4.24

At the end of the experiment, 300 individuals from each group were subjected to biometric measurements (BW, SL and TL) using the same technological equipment used at the beginning of the trial. The erosion of fins was assessed in 90 individuals from each group described above. The state of erosion was assessed by qualified personnel and divided into four categories (0–4), and their percentage distribution was calculated for each group according to (Policar et al., 2016). Blood samples were drawn from 12 individuals from each experimental group (36 fish in total), and these fish were, as at the beginning, dissected for internal organ inspection and subsequent determination of somatic indices. The following production parameters were calculated according to the following formulas from the determined BW, TL and SL: number of surviving fish, consumed feed, number of days of trial and weight of dissected organs at the both beginning and termination of the trial:

The specific growth rate (SGR) (%. d^{-1}) was calculated as follows:

$$SGR = \frac{\ln FBW - \ln IBW}{t} x \ 100$$

SR (%) was calculated as follows:

$$SR = \frac{NF}{NI} x \ 100$$

Weight gain (%) was calculated as follows:

$$WG = (\frac{FBW}{IBW} x \ 100) - 100$$

The feed conversion ratio (g. g^{-1}) was calculated as follows:

$$FCR = \frac{F}{BG}$$

The condition factors were calculated as follows:

$$CF = \frac{BW}{TL^3} \times 100$$

The hepatosomatic index (%) was calculated as follows:

$$HSI = \frac{WL}{BW} x \ 100$$

The IPFI (%) was calculated as follows:

$$IPFI = \frac{WIPF}{BW} x \ 100$$

The spleensomatic index (%) was calculated as follows:

$$SSI = \frac{WS}{BW} x \ 100$$

The gonadosomatic index (%) was calculated as follows:

$$GSI = \frac{WG}{BW} x \ 100$$

The RGL was calculated as follows:

$$RGL = \frac{GL}{SL}$$

In all the formulas, the following measurements and records were used: initial and final body weight (IBW and FBW), final total length (FTL), number of days of the trial (t), number of fish in the sample (N), final number of fish (NF), initial number of fish (NI), feed consumption (F), biomass gain (BG), total length (TL), standard length (SL), body weight (BW), weight of the liver (WL), weight of IPFI (WIPF), weight of spleen (WS), weight of gonad (WG) and gut length (GL).

2.6 Economic evaluation

To calculate production costs for pikeperch juveniles, the following cost categories were evaluated: feed, electricity, tap water, oxygen, personnel (including insurance and tax), stocking material, chemicals and depreciation costs. The final production cost was compared with the final number of produced fish to calculate the exact production cost per fish. Personal cost was calculated on the basis of the time spent working with each system. In case of three tanks in RAS it was on average 60 minutes per day. In case of IPRS it was 45 minutes per day. In case of the POND price of personell was calculated to cover the personal cost during the harvest, sorting the fish after harvest and occasional work like cleaning the ouflow and inflow of the ponds during growing season. To estimate the production cost of pikeperch in a polyculture system, personal labor, electricity, and depreciation expenses were evenly allocated among the cultured fish species (common carp, pikeperch, rudd, and tench broodstock), with each group assigned 25% of the total operational costs, excluding those related to stocking material. Although pikeperch accounted for only 2.38% of the total harvested biomass at the termination of the experiment, this imbalance was offset by its disproportionately higher share at the beginning of the production cycle, when pikeperch represented 42.3% of the total stocked biomass due to the more complex and demanding nature of its stocking process.All the time spend on data collection, sampling, calculating of uneaten feed etc was not included as it does not reflect a standard production practices and it would artificially increase production cost of the fish in this study

2.7 Statistical analyses

Data were analysed using the Rstudio software (R Core Team, 2014). Before the statistical analysis, several preliminary tests were conducted. The Shapiro–Wilk test was used to determine the normality of the residuals, whereas Levene's test was employed to inspect the homogeneity of variance. Furthermore, the Kolmogorov–Smirnov test was used to assess data normality. The production parameters were compared using one-way ANOVA, with a significance margin set at $P < 0.05$. The homogeneity of the data was assessed using the Tukey's Honestly Significant Difference method. All data are presented as the mean ± standard deviation (SD).

3 Results

3.1 Growth and feed utilisation of the pikeperch

Pikeperch juveniles cultured in different rearing systems achieved significantly different growth rates. The highest FBW was 190.0 ± 67.72 g (RAS, almost quadrupled their BW during the experiment) compared with 121.0 ± 36.39 g (IPRS, more than doubled their BW during the experiment), and the lowest FBW was 62.5 ± 19.26 g in the POND group, which was fully correlating with the FTL of 278.6 ± 32.5, 249 ± 23.20 and 208 ± 15.76 mm, respectively. The same trend was observed in weight gain, which was the highest (268.0% ± 21.23%) in the RAS, 132.7% ± 1.25% in the IPRS and the lowest (28.3% ± 18.56%) in POND. FCR reached 1.0 ± 0.03 and 1.6 ± 0.10 in the RAS and IPRS, respectively. In terms of SGR, this result corresponds to the highest value (0.7 ± 0.01%.day^{-1}) in the RAS, 0.4 ± 0.02%.day^{-1} in the IPRS, and the lowest value (0.1 ± 0.08%.day^{-1}) in the POND group. Regarding CF, fish from the RAS had the highest CF value of 1.3 ± 0.10 compared with 1.2 ± 0.11 in the IPRS and 1.1 ± 0.17 in the POND group. The total mean BG in the RAS was 53,120 g, whereas it was 26,208 g in the IPRS. In the ponds, no gain in biomass was observed owing to the low SR of pikeperch juveniles. All mentioned production data are presented in Table 2.

3.2 Growth of other fish species in pond polyculture

In the polyculture regime of stock in ponds, other fish species also displayed growth. The highest growth rate was observed in common carp, which increased from an IBW of 94.3 g to an FBW of 515.0 ± 75.0 g, resulting in a WG of 446.4% and an SGR of 1.0 ± 0.1%.day^{-1}. The tench reached an FBW of 908.3 ± 53.6 g from an IBW of 896.5 ± 27.4 g, resulting in a WG of 1% and an SGR of 0.052%.day^{-1}. The broodstock of rudd reached almost a similar result, growing from an IBW of 171.1 ± 0.9 g to an FBW of 183.7 ± 9.6 g, resulting in a WG of 7.3% and an SGR of 0.042%.day^{-1}.

3.3 Survival rate

The SRs were statistically similar between the RAS and IPRS (83.9% ± 3.65% and 88.9% ± 0.81%, respectively). The SR in the pond was significantly lower (5.9% ± 4.11%). The mean BW of morbid fish in the RAS was 68.9 g, whereas that in the IPRS was 42.2 g. Moreover, the size of morbid fish in the IPRS decreased throughout the trial, as shown in Figure 4, although the fish displayed increasing growth and BW. The dynamics of mortality differed between the RAS and IPRS, as shown in Figure 5. The survival rates of other cultured fish in polyculture stock in ponds were as follows: common carp, 70.3% ± 8.3%; tench, 71.8% ± 15.9% and rudd, 64% ± 28.6%.

3.4 Fin erosion of pikeperch

During the assessment of fin erosion, only categories 0 (no damage) and 1 (minor damage) were observed. Categories 2,3 and 4 were not found on inspected individuals indicating that the fish suffered from only minor fin erosion. From the 90 assessed individuals in each group, 68.9% ± 12.86% in the RAS, 40.0% ± 7.2% in the IPRS and 27.2% ± 16.5% in the POND group were affected by the fin erosion in category 1. Fish from the RAS group mostly experienced erosion (category 1) of the caudal fin (25.6% ± 3.1%), first dorsal fin (11.3% ± 4.10%) and second dorsal fin (26.7% ± 2.72%). Fish from the IPRS mostly suffered from the erosion of both pectoral fins (8.89% ± 1.54% left; 11.3% ± 1.54% right) and caudal fins (11.1% ± 4.16%). Fish from the POND group exhibited uneven erosion across all fins, with the highest frequency of erosion (category 1) found on the caudal fin (7.8% ± 6.85%), left pectoral fin (9.06% ± 5.50%) and right ventral fin (6.67% ± 7.20%). A detailed description of the erosion of all fins is presented in Table 3.

3.5 Somatic indices of pikeperch

Analysis of the somatic indices of cultured pikeperch showed the following: fish from the RAS displayed significantly higher

TABLE 2 Production markers of pikeperch juveniles in three different rearing systems after 24 weeks of rearing.

Parameter	Initial	RAS	IPRS	POND	F-statistics	P-value
FTL (mm)	197 ± 11.6^{c}	278.6 ± 32.6^{a}	249 ± 23.2^{b}	208 ± 15.8^{c}	F(3,784) = 37.2	P < 0.005
FBW (g)	51.6 ± 10.3^{c}	190.0 ± 67.7^{a}	121 ± 36.4^{b}	62.5 ± 19.3^{c}	F(3,784) = 312	P < 0.005
WG (%)	–	268.0 ± 21.2^{a}	132 ± 1.25^{b}	28.3 ± 18.6^{c}	F(2,6) = 109	P < 0.005
SR (%)	–	83.90 ± 3.65^{a}	88.9 ± 0.81^{a}	5.91 ± 4.11^{b}	F(2, 6) = 421	P < 0.005
CF	1.1 ± 0.10^{c}	1.3 ± 0.10^{a}	1.2 ± 0.11^{b}	1.1 ± 0.17^{c}	F(3,784) = 67.5	P < 0.005
SGR (%.d^{-1})	–	0.7 ± 0.01^{a}	0.4 ± 0.02^{b}	0.1 ± 0.08^{c}	F(2,6) = 57.0	P < 0.005
FCR (g.g^{1})	–	1.0 ± 0.03^{a}	1.6 ± 0.10^{b}	–	F(1,4) = 70.9	P < 0.005

FTL, Final total length; FBW, Final body weight; WG, Weight gain; SR, Survival rate; CF, Condition factor; SGR, Specific growth rate; FCR, Feed conversion ratio.
Values with different superscripts *(a, b, c)* differ significantly (*p* < 0.05).

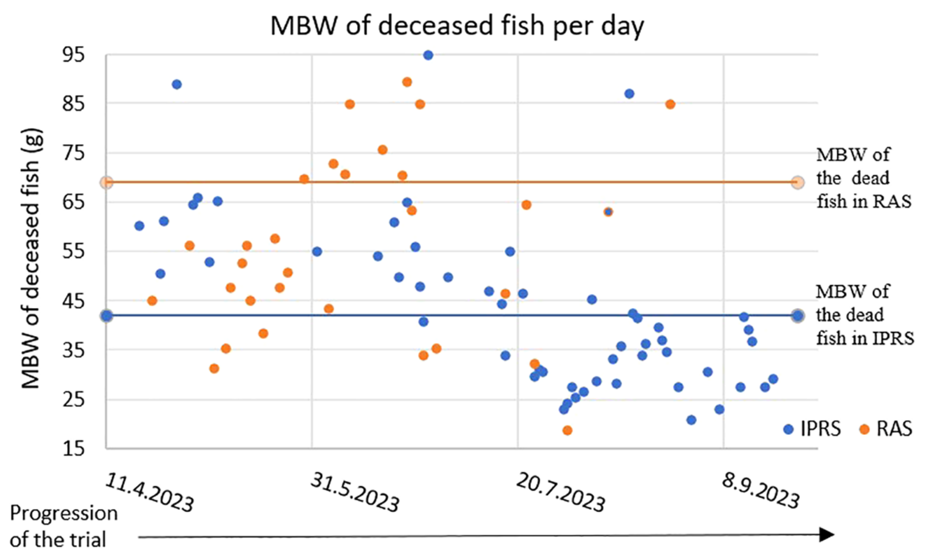

FIGURE 4
Mean body weights of deceased individuals during the experiment in IPRS and RAS groups.

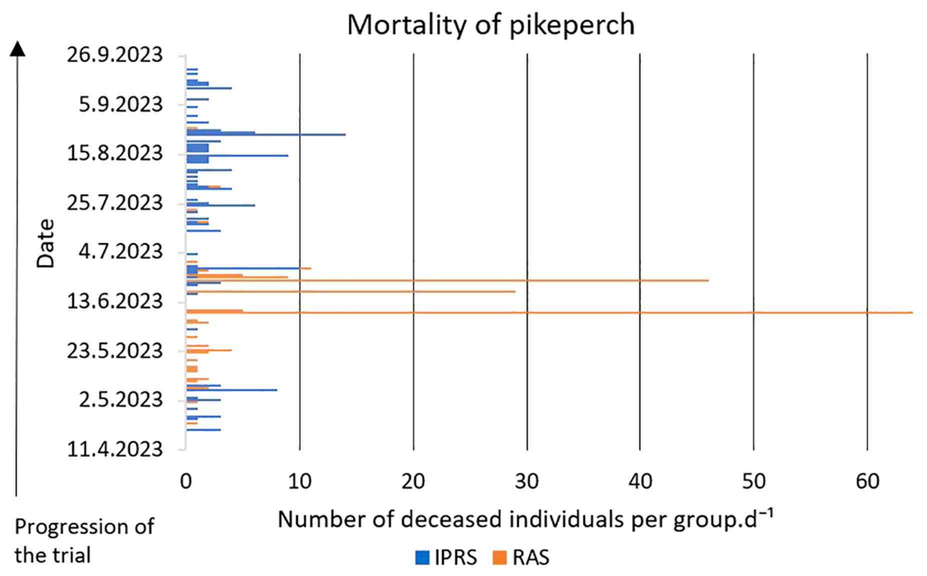

FIGURE 5
Dynamics of mortality in the experimental IPRS and RAS, episodes of bacterial infection in RAS (8.6., 17.6. and 22.6.) and increase of mortality in IPRS due to the water quality in the pond in late summer and increased heterogeneity among the tank stock.

IPFI together with the IPRS compared with POND-raised fish. RAS-raised fish also exhibited significantly enlarged livers (higher HSI) compared with the other groups. Consequently, the spleen (SSI) was significantly smaller in the RAS and larger in the POND group. The RGL of POND-raised fish was significantly higher than that of the RAS and IPRS-raised fish. No statistically significant differences were found in the GSI. All parameters are described in Table 4.

3.6 Biochemical parameters of pikeperch blood

The plasma levels of TP, ALB, GLOB, NH_3 and LIPA were within the ranges normally found in pikeperch in good conditions (Kolářová and Velíšek, 2012). TP was statistically higher in fish from the RAS and IPRS compared with that from the POND group. The concentration of ALB differed significantly among all the tested

TABLE 3 Frequency of fin erosion on juvenile pikeperch reared in different systems.

Parameter	Initial	RAS	IPRS	POND
LP (%)	3.33 ± 2.72	1.10 ± 1.60	8.89 ± 1.54	9.06 ± 5.50
RP (%)	5.56 ± 1.57	1.12 ± 1.54	11.3 ± 1.54	1.12 ± 1.50
LV (%)	0.00 ± 0.00	1.09 ± 1.52	0.00 ± 0.00	1.28 ± 1.81
RV (%)	0.00 ± 0.00	1.10 ± 1.50	2.31 ± 1.52	6.67 ± 7.20
FD (%)	8.89 ± 1.58	11.3 ± 4.10	2.20 ± 1.62	1.28 ± 1.81
SD (%)	17.8 ± 1.62	26.7 ± 2.72	2.22 ± 3.14	0.00 ± 0.00
Ca (%)	16.7 ± 2.72	25.6 ± 3.14	11.1 ± 4.16	7.78 ± 6.85
An (%)	7.78 ± 4.16	1.00 ± 1.58	2.22 ± 3.14	0.00 ± 0.00

LP, Left Pectoral fin; RP, Right Pectoral fin; LV, Left Ventral fin; RV, Right Ventral fin; FD, First Dorsal fin; SD, Second Dorsal fin; Ca, Caudal fin; An, Anal fin

groups, with the highest levels in the RAS and the lowest in the POND group. GLOB was statistically higher in the RAS compared with the POND group. GLU was statistically the highest in the IPRS and exceeded the values normally determined in pikeperch under good conditions. AMY showed statistically significant differences among all the groups, being the highest in the RAS and the lowest in the POND group. Fish from POND were the only ones not exceeding the normal values of AMY for pikeperch in good conditions. TCHO did not show any statistically significant differences among the groups. LIP was significantly the highest in the POND group. NH_3 was the highest in the RAS but did not exceed the normal values for pikeperch. TG levels in pikeperch across all the groups, including the fish at the start of the test, were higher than the reported normal values for pikeperch. Among the groups, the TGs were statistically lower in the POND group, which only slightly exceeded the values for pikeperch in good conditions. Increased activity of the liver enzyme ALP was higher in fish from the POND group, with ALP levels in the POND group being two times higher than those in the upper range of pikeperch in good conditions. Pikeperch from the IPRS had the highest AST values compared with those from the POND group and RAS. All biochemical parameters are listed in Table 5.

3.7 Economical evaluation

The evaluation of each part of the production cost revealed the following. The highest share represents stocking and personnel costs. These categories are closely followed by feed, depreciation

TABLE 4 Somatic indexes of experimental pikeperch from different production systems after 24 weeks of rearing.

Parameter	Initial	RAS	IPRS	POND	F-statistics	P-value
SSI (%)	0.10 ± 0.02^{b}	0.01 ± 0.03^{a}	0.04 ± 0.02^{ab}	0.07 ± 0.06^{b}	F(3,42) = 522	P < 0.005
HSI (%)	1.58 ± 0.21^{a}	1.34 ± 0.23^{a}	1.05 ± 0.12^{b}	0.87 ± 0.37^{b}	F(3,42) = 51.6	P < 0.005
IPF (%)	3.23 ± 1.06^{a}	3.61 ± 0.91^{a}	3.12 ± 0.66^{a}	0.07 ± 0.18^{b}	F(3,42) = 50.2	P < 0.005
GSI (%)	0.34 ± 0.18	0.52 ± 0.42	0.70 ± 0.73	0.54 ± 0.60	F(3,42) = 0.76	P = 0.524
RGL	0.47 ± 0.08^{c}	0.67 ± 0.10^{b}	0.69 ± 0.10^{b}	0.80 ± 0.10^{a}	F(3,42) = 155	P < 0.005

SSI, Spleensomatic index; HSI, Hepatosomatic index; IPFI, Intraperitoneal fat index; GSI, Gonadosomatic index; RGL, Relative gut length.
Values with different superscripts *(a, b, c)* differ significantly ($p < 0.05$).

TABLE 5 Biochemical parameters of the blood of pikeperch juveniles.

Parameter	Initial	RAS	IPRS	POND	F-statistics	P-Value
TP ($g.L^{-1}$)	34.7 ± 2.06^{a}	37.3 ± 5.56^{a}	32.4 ± 2.97^{a}	24.8 ± 9.15^{b}	F (3,42) = 6.56	P < 0.005
ALB ($g.L^{-1}$)	3.90 ± 1.52^{c}	8.33 ± 1.87^{a}	5.92 ± 1.16^{b}	2.83 ± 2.17^{c}	F (3.42) = 18.3	P < 0.005
GLU ($mmol.L^{-1}$)	4.99 ± 1.83^{c}	11.8 ± 4.12^{b}	20.5 ± 6.51^{a}	$9.47 \pm 4.76^{b,c}$	F (3,42) = 25.9	P < 0.005
AMY ($\mu kat.L^{-1}$)	11.7 ± 3.04^{b}	17.5 ± 3.60^{a}	10.1 ± 1.22^{b}	7.00 ± 2.74^{c}	F (3,42) = 21.1	P < 0.005
LIPA ($\mu kat.L^{-1}$)	0.45 ± 0.06^{a}	0.48 ± 0.05^{a}	0.44 ± 0.06^{a}	0.56 ± 0.08^{b}	F (3,42) = 6.68	P < 0.005
TCHO ($mmol.L^{-1}$)	4.46 ± 3.87	2.87 ± 1.17	2.29 ± 0.58	3.73 ± 1.96	F (3,42) = 19.6	P = 0.049
ALP	1.51 ± 0.89^{b}	1.17 ± 0.52^{b}	0.72 ± 0.42^{b}	2.77 ± 1.25^{a}	F (3,42) = 10.5	P < 0.005
AST	3.05 ± 2.04^{a}	1.29 ± 0.61^{b}	2.68 ± 1.06^{a}	$2.12 \pm 0.91^{a,b}$	F (3,42) = 6.87	P < 0.005
GLOB ($g.L^{-1}$)	30.8 ± 1.87^{a}	28.9 ± 3.80^{a}	$26.5 \pm 2.0^{a,b}$	21.9 ± 7.40^{b}	F (3,42) = 11.3	P < 0.005
TG ($mmol.L^{-1}$)	$7.61 \pm 3.02^{a,b}$	9.08 ± 4.89^{a}	$5.71 \pm 2.4^{a,b}$	4.41 ± 5.65^{b}	F (3,42) = 2.43	P = 0.092
NH_3 ($\mu mol.L^{-1}$)	496.3 ± 95^{b}	871.0 ± 263^{a}	526.8 ± 65^{b}	602.6 ± 172^{b}	F (3,42) = 7.23	P < 0.005

TP, Total protein; ALB, Albumin; GLU, Glucose; AMYL, Amylase; LIPA, Lipase; TCHOL, Total cholesterol; ALP, Alanine aminotransferase; AST, Aspartate aminotransferase; GLOB, Globulin; TG, Triglycerids; NH_3, Ammonia.
Values with different superscripts *(a, b, c)* differ significantly ($p < 0.05$).

and electricity costs (except for the POND group). In the RAS, one of the most important production costs is related to oxygen consumption. Conversely, no oxygen was administered during the trial period in the IPRS and POND groups. Finally, the less significant categories of production costs included consumed tap water and chemicals. Production costs were then corelated with the number of produced fish. This calculation resulted in the following production costs per juvenile: RAS = 4.24 EUR per fish (FBW 190 g), IPRS = 3.05 EUR per fish (FBW 120g) and POND = 21.98 EUR per fish (FBW 62.5g). The production cost of pikeperch juveniles in RAS 22.3 $EUR.kg^{-1}$. While in IPRS it was 25.4 $EUR.kg^{-1}$ and in POND351.9 $EUR.kg^{-1}$. The production costs of POND-raised juveniles are presented as an illustration of the economic losses induced by the low SRs. All categories contributing to the final production cost are presented in absolute numbers (EUR) and as percentages (%) in Table 6.

4 Discussion

In recent years, an unprecedented increase in energy costs has been observed across Europe. New and less energy-demanding approaches to fish culture should be tested and implemented alongside current aquaculture technologies. Although energy-intensive, RASs still offer feasible solutions. Nevertheless the search for new production methods must be encouraged. The presence of vast pond infrastructure in Central and Eastern Europe opens the possibility for diversification through pond aquaculture along with new technological equipment such as the IPRS. To provide comprehensive information on the pros and cons of fish keeping in the RAS, POND and the hybrid IPRS, this study was conducted. Herein, juveniles of pikeperch originating from POND–RAS combined production (Policar et al., 2013) were cultured in the RAS, IPRS and POND to determine growth, feed utilisation, survival and welfare of cultured fish. The SGR of the experimental fish in this study reached $0.7\%.d^{-1}$ (RAS) and $0.4\%.d^{-1}$ (IPRS) compared with $0.6\%.d^{-1}$ (RAS) and $0.6\%.d^{-1}$ (IPRS) reported by Nagy et al. (2022). The lower SGR may reflect differences in the climate of Southeast Hungary (study published by Nagy et al., 2022) and South Bohemia (present study),particularly in the temperature during the growing season. Moreover, the experiment conducted in Hungary began in June and ended in September, whereas the experimental period in this study began in April and ended in September. At the beginning of the trial, a lower DFR was applied because of the physiological activity of the pikeperch, and their appetite was reduced owing to the lower water temperature in the pond where the IPRS was situated. The SGR of RAS-raised fish was slightly lower in this study ($0.7\%.d^{-1}$) than in the other studies focusing on intensive RAS-based pikeperch rearing (Pěnka et al., 2023, 2021, Rónyai and Csengeri, 2008). Pikeperch juveniles in the POND group achieved only 28.3% ± 18.56% WG and an 0.1 ± $0.08\%.day^{-1}$ SGR. This was likely due to unsuccessful adaptation and an inability to hunt prey fish. Feed utilisation in this study resulted in FCR = 1 $g.g^{-1}$ (RAS) and 1.6 $g.g^{-1}$ (IPRS), which is consistent with the findings of other studies on RAS-cultured juvenile pikeperch (Pěnka et al., 2023, 2021; Zimmerman et al., 2019). Nagy et al. (2022) reported an FCR of 2.1 $g.g^{-1}$ for IPRS-raised fish. A possible explanation for the high FCR in the IPRS, observed in both this study and the one conducted by Nagy et al. (2022), is that fish reared in outdoor conditions were fed to satiation but were unable to fully digest dry pelleted feed because lower oxygen saturation during the second part of the experiment (mornings before sunrise inlate July and August) resulting in slower growth. Additionally, the large tanks in the IPRS combined with the water flow may have discarded some uneaten feed, artificially increasing the observed FCR. Over the last 20 years, extensive research on feed management in RAS-raised pikeperch production has been conducted (Schulz et al., 2007; Rónyai and Csengeri, 2008; Wang et al., 2009; Kowalska et al., 2015; Pěnka et al., 2023). However, no studies on feed management in IPRS-based pikeperch production have yet been published. Owing to differences in lighting regimes, light intensity, water temperature and quality, turbidity and stocking density, different feeding management practices should be developed and applied to improve feed utilisation in the IPRS. In the RAS, the uneaten feed was properly recorded and subtracted to calculate the exact feed intake. In the ponds, natural predation of prey fish led to an unknown feed intake, which excluded this experimental group from the determination of FCR.

The SR is one of the most important production parameters influencing the feasibility of pikeperch culture. The SRs of fish in the IPRS and RAS were statistically similar (88.9% and 83.9% respectively). However, the mortality of fish in the IPRS differed by the size of the deceased fish and the dynamics of mortality, which mostly occurred in two periods. The first period occurred 2 weeks

TABLE 6 Production costs of pikeperch juveniles raised in three different production systems.

	RAS		IPRS		POND	
	EUR	%	EUR	%	EUR	%
Feed	629	12	491	12	0	0
Tap water	69	1	0	0	0	0
Electricity	380	7	320	8	12.5	0.6
Oxygen	642	12	0	0	0	0
Stocking fish	1786	33	1786	44	1786	92
Chemicals	135	3	77	2	0	0
Personal cost + insurance and tax	1375	26	1069	26	102	5.3
Depreciation	317	6	317	8	34	1.8
FBW (g)	190.0		121.0		62.5	
Survival (pcs)	1258		1333		88	
Euros per juveniles	4.24		3.05		21.98	
Euros per 1kg of juveniles	22.3		25.4		351.9	

FBW, final body weight of the raised fish
All categories are displayed as absolute numbers (in Euros) and as a percentual share (%).

after acclimation at the beginning of the experiment. During the first period, larger fish with BW of >50 g exhibited mortality, likely because of adaptability issues. During the experiment heterogeneity in the tanks was gradually increasing and resulted in higher mortality in the second part of the experiment, as shown in Figure 5. During the second part (second mortality event) of the experiment, small and malnourished fish weighing <40 g were found dead (Figure 4). The final MBW of all deceased fish found during the experiment was 42.2 g. In a study conducted by Nagy et al. (2022), the SR of IPRS-raised fish was 96%. The observed disparity is likely connected to the larger size of the experimental fish in Hungarian experiment, which naturally have a lower mortality rate and cannibalism is suppressed. In the RAS, the dynamics of mortality were different. During the first half of the experiment, three episodes of bacterial infection occurred, and 76.6% of all the deceased individuals died in these three mortality events before the infection was suppressed. The episodes of bacterial infection did not differ between the sizes of the experimental fish and resulted in a higher MBW in the RAS group (68 g). Because the experiment was designed to evaluate the pros and cons of each production system and the overall mortality in all the three mortality events combined did not reach 10% of all stocked fish, the experiment was continued. As stated by Yanong (2012), the risk of a rapid disease outbreak in the RAS represents a major drawback of keeping fish in the RAS. The SR in the present study is, therefore, lower than those of other studies focusing on juvenile pikeperch rearing or early grow-out (Nyina-Wamwiza et al., 2005; Pěnka et al., 2023, 2021; Rónyai and Csengeri, 2008). Nevertheless, the experiment presented in this study was conducted on a larger scale than the other mentioned studies and is, therefore more comparable with commercial production in intensive farms, where elimination of bacterial diseases is more complicated. SRs for both the IPRS and RAS were in accordance with those of Fontaine et al. (1995), suggesting the SRs of Eurasian perch (*Perca fluviatilis*) in the RAS of up to 90%–100% and 70%–80% in cage culture during the growing season in a lake. The disparity in the SRs between cages and modern the IPRS units was likely caused by improvements in water circulation and quality between cages and modern IPRS. The SR of pikeperch in the pond was significantly lower, at only 5.9% ± 4.11%, and varied between ponds. Such a low SR probably occurred for the following reasons. The ponds used in the experiments were highly turbid during the second part of the experiment (late summer) and contained excessive amounts of algae. Although the measured oxygen levels did not decrease to <60%, morning oxygen deficiencies were common. Nevertheless no dead fish were found during the morning oxygen deficiencies. As previously stated, all fish stocked in the experiment originated from RAS. These demanding adaptations likely negatively affected their survival. The last factor to be considered is fish predators. This issue likely affected other members of the polyculture stocking as well. The survival rates of carp (70.3%) and tench (71.8%) were lower than the normall SRs of a second year carp and broodstock of tench in ponds (75% and 90%, respectively) as calculated and published by Hartman and Regenda (2016). Because the survival rate of pikeperch juveniles in ponds was the lowest, the POND group is presented as an unfortunate example of the unpredictability of pikeperch production in ponds. Although 80%–88% of all farmed fish in the Czech Republic are produced through pond aquaculture (Vavrečka et al., 2019), the outcome of pond rearing is unpredictable and may sometimes be unsuccessful. This is particularly true for sensitive, high-oxygen-demanding predatory species such as the pikeperch. Herein, most of the pond's production capacity was used by fish species other than pikeperch. The growth of common carp was particularly intensive.

Fin erosion is one of the easiest factors to assess when evaluating fish health and physiological status (North et al., 2006). Eroded fins can be sites for microbial infection, affecting consumer acceptance of the whole fish and reducing its economic value (Stejskal et al., 2011). The RAS group had the highest frequency of damage to the caudal fin. The most damaged fins in the RAS were the dorsal fins and caudal fin, as also reported by Pěnka et al. (2023) and Policar et al. (2016). A similar situation was observed at the beginning of the trial, where fish from the RAS also displayed the highest degree of fin erosion on both the dorsal and caudal fins. Throughout the experiment, the quality of the dorsal and caudal fins in the IPRS improved, likely due to the decreased stocking density of the pikeperch. Fish kept at higher densities in the RAS are more susceptible to fin erosion due to aggressive feeding behaviours, abrasion from the tank and other fish and constant social interaction (Stejskal et al., 2011). An increased erosion of the pectoral fins in IPRS based individuals was found. Because pikeperch prefers lower light intensities, this preference influences their behaviour in the tanks of the RAS and IPRS. In the IPRS, situated outdoors during the growing season, pikeperch spend most of their time near the bottom of the tanks. Fish were forced to take shelter from direct sunlight for 10–16 h per day (light phase). This naturally induced behaviour makes the fish spend most of their time in the presence of excessive biofilm. The continuous movement of the pectoral fins, necessary to maintain the fish's stable position in the water column, results in frequent contact with the substrate and associated biofilm. Over time, this repetitive motion contributes to gradual fin erosion. To address this issue, tanks should be covered to provide more suitable light intensity in the IPRS. This hypothesis was confirmed by the increased erosion of the pectoral and ventral fins of POND-based individuals living in the turbid conditions of the pond. Similar erosion of pectoral and ventral fins was also discovered in POND group and may reflect bottom dwelling behaviour while still could be partially a residual damage from the RAS origin. Conversely, fish from the IPRS displayed very low erosion of both the dorsal fins, probably caused by decreased stocking density compared with RAS-raised fish. POND-raised fish also showed the erosion of the caudal fin, probably as residual damage from their RAS origin.

Assessing the physiological status of fish is crucial for identifying issues related to industrial farming (Sarameh et al., 2013; Falahatkar et al., 2014). Somatic indices are important parameters for assessing fish health. Increased IPFI content in IPRS- and RAS-based fish is correlated with pellet use and decreased activity in smaller rearing spaces and feeding intensity. Fish from POND showed almost no IPFI, likely because of their inability to feed on feed fish in the turbid conditions of the pond and their more active lifestyle. Furthermore, individuals are able to hunt prey fish digested feed with lower fat levels (live fish compared with pellets). The significantly increased liver size suggests higher digestive and metabolic activity in RAS pikeperch. Similar results were reported by Policar et al. (2016), showing significantly enlarged livers (HSI 2.0%) and fat deposits (IPFI 3.61%) in RAS-raised juveniles compared with POND-raised juveniles (0.8% and 0.3%, respectively).

The biochemical analysis of blood revealed statistical differences in all parameters except for TCHOL. For TP, ALB, AST and GLOB, ranges of values for pikeperch were observed under good conditions, although statistical differences were observed. However, GLU levels reported for pikeperch in good conditions (5–10 mmol.L^{-1}; Kolářová and Velíšek, 2012) were exceeded in all the groups, with the IPRS-raised pikeperch showing almost double the levels. An increased blood glucose concentration is generally an indicator of stress in fish and may reflect a rather stressful final harvest of otherwise unbothered fish in IPRS. Higher AMY concentrations compared with those in pikeperch under good conditions were found in fish from the RAS and IPRS. The differences among all the tested groups were statistically significant, with the highest AMY in the RAS and the lowest in the POND group. Increased amylase concentrations reflect higher carbohydrate levels in pellets than in POND-raised fish and their natural prey.

The parameters ALB and GLOB indicate the fish condition and especially GLOB could be indicators of health of the liver. Both parameters display the same trend (POND is the lowest, RAS is the highest) and may suggest beginning of the liver damage. This correlation was associated with the different fish conditions and feeding methods of the tested groups. The ALP was statistically the highest in the POND group compared with the RAS and IPRS. ALPs affect membrane transport, glycogen metabolism and protein synthesis. The increased ALP level in the POND group may be related to the relative starvation of the fish compared with that in the RAS and IPRS. An ALP level of 2.77 in POND-raised fish reflects starvation and is directly connected to virtually non-existent fat reserves (IPFI of 0.07% ± 0.18%) and a high mortality rate. A significant difference in NH_3 concentration was found between the IPRS (526 μmol.L^{-1}) and POND group (602.6 μmol.L^{-1}) compared with the RAS (870.7 μmol.L^{-1}, within the range normally found in pikeperch in good conditions) (Kolářová and Velíšek, 2012). This parameter reflects more intensive feed consumption and reduced activity in the limited space of smaller RAS tanks.

The production costs of pikeperch differed significantly between the groups. The production costs of fish in the IPRS are not burdened with the same expenses as those in the RAS. The lack of oxygenation in the IPRS, along with lower chemical, feed and electricity consumption, provides an economic advantage. Reduced personnel costs due to less demanding maintenance resulted in lower costs for pikeperch juveniles raised in the IPRS. This result was achieved mainly because SR was slighty higher in the IPRS that in the RAS. Further analysis of production costs revealed a disparity between the cost of producing pikeperch per individual and kilogram, as both methods of fish pricing are used in aquaculture industry. Recalculating the production cost of pikeperch showed that fish raised in large scale RAS were produced at 22.4 EUR per kg, whereas fish raised in the IPRS were produced at 25.4 EUR per kg. This disparity was caused by the more rapid growth of the fish in the RAS achieving significantly higher body weight over the same time period. Final production cost was calculated with the intention to sell the juveniles. If the production period would be prolonged enough to reach a market sized fish then a more rapid growth of fish kept in RAS would probably turn into the advantage of RAS production.

At this stage of IPRS development, the production costs are higher than anticipated. The higher cost of the IPRS-raised pikeperch production will be reduced in the future through the optimisation of electricity consumption, improved aeration, feed distribution and feeding management. Although the full optimisation of the IPRS under Central European conditions is not yet finished, the production cost per one juvenile was lower for the IPRS than for the RAS (3.05 EUR and 4.24 EUR, respectively). The production cost of pikeperch juveniles in polyculture POND was affected by low SRs, which resulted in unacceptable prices. The calculation of production costs in pond culture illustrates the economic losses caused by the low survival of stocking fish.

This experiment found that the IPRS offers better feasibility for producing pikeperch juveniles compared with pond production systems and is similar to the RAS culture. The development of the IPRS pikeperch culture can, in the future, increase the capacity for producing juvenile stocking material and marketable-sized pikeperch, particularly in countries with large pond areas. Stocking open waters with fish raised in the IPRS would also benefit the process because these fish require less demanding adaptations to outdoor systems than RAS-raised fish. Fish raised in the IPRS only need to switch from feeding on pellets to hunting for prey, whereas RAS-raised pikeperch also need to cope with major changes in water quality (turbidity, oxygen saturation and bacterial load).

5 Conclusion

The IPRS is an appropriate method for pikeperch juvenile production during the growing season. Despite the slower growth of the fish, the significantly reduced production cost of juveniles in the IPRS compensates for the difference compared with RAS production. Similar SR and comparable physiological statuses of fish in both the RAS and IPRS further ensure the feasibility of pikeperch production in the IPRS, especially in countries with large pond areas (Central and Eastern Europe or Asia). To further increase the value of IPRS-raised pikeperch, feeding management should be optimised to enhance feed utilisation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

All the experimental manipulations compliedwith the valid legislative regulations in the CzechRepublic (Law No. 166/1996 and No. 246/1992); thepermit was issued to No. 68668/2020-MZE-18134. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

VK: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing – original draft. TPě: Data curation, Software, Visualization, Writing – review & editing. OM: Conceptualization, Data curation, Software, Visualization, Writing – review & editing. JK: Data curation, Formal analysis, Methodology, Writing – review & editing. JR: Conceptualization, Methodology, Visualization, Writing – review & editing. TPo: Conceptualization, Data curation, Funding acquisition, Project administration, Supervision, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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