Aquaculture International (2024) 32:6487–6499
https://doi.org/10.1007/s10499-024-01475-7

RESEARCH

Effect of different feed rations on growth performance in various size classes of juvenile pikeperch, *Sander lucioperca*

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Received: 15 February 2024 / Accepted: 18 March 2024 / Published online: 28 March 2024

Abstract

The effect of different feed rations on RAS-based pikeperch juveniles' growth parameters was studied. Juvenile pikeperch were reared in three separate experiments (I, II, and III) at a temperature of 24 °C with initial body weights of the fish at 1.3, 9.4, and 25.6 g, respectively. Four applied feed rations increased by 0.5% in each experiment: 3.0, 3.5, 4.0, and 4.5% of body weight per day (BW day^{-1}) in experiment I; 2.0, 2.5, 3.0, and 3.5% BW day^{-1} in experiment II; 1.0, 1.5, 2.0, and 2.5% BW day^{-1} in experiment III. Each experiment in triplicates lasted 28 days. The fish were reared in tanks with working volumes of 1.0 m^3 each. All experiments were performed in the same recirculating aquaculture system. The stocking density in experiments I, II, and III was 800, 400, and 200 individuals per tank, respectively. The results of experiment I showed the highest specific growth rate (SGR), weight gain (WG), and biomass gain at the feed ration of 4.5% BW day^{-1} ($P<0.05$). In experiment II, feed ration from 2.5 to 3.5% BW day^{-1} showed the highest final weight ($P<0.05$). In experimental III, feed ration of 2.0 and 2.5% BW day^{-1} showed the highest final weight, SGR, and WG ($P<0.05$). Only in experiment III, based on SGR and WG, second-order polynomial regression showed that the optimal feed ration for pikeperch was 2.35–2.39% BW day^{-1}.

Keywords Feeding rates · Growth · *Sander lucioperca* · Recirculating aquaculture systems

Handling Editor: Brian Austin

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Introduction

Pikeperch, *Sander lucioperca* (Linnaeus), is a predatory fish of the family Percidae that is common in the waters of parts of Europe and Asia (Kottelat and Freyhof 2007; Kestemont et al. 2015). This fish is popular among consumers for its good quality meat, high protein and low-fat contents, and its small number of intermuscular bones (Jankowska et al. 2003; Tönißen et al. 2022). Consumer demand for pikeperch is mainly met by commercial fisheries and pond aquaculture. Evidence of the demand and expansion of this species is that, in the years 2011–2021, global commercial fisheries pikeperch catches grew from approximately 17,000 to 23,000 tons and global pikeperch inland aquaculture production increased from 787 to 1992 tons (FAO 2023). In some European countries, the popularity of pikeperch has resulted in the increased intensification of commercial aquaculture production at facilities with recirculating aquaculture systems (RAS) (Policar et al. 2019).

The growth of cultured fishes depends on many factors, including temperature (Desai and Singh 2009; Swirplies et al. 2019), feed composition (Nyina-wamwiza et al. 2005; Schulz et al. 2008; Bochert 2022), stocking density (Liu et al. 2019; Kozłowski and Piotrowska 2023), and feeding frequency (Zakęś et al. 2006; Pěnka et al. 2023). In aquaculture, the amount of feed provided to fish is the most important since it significantly influences growth parameters and feeding efficiency (Cho et al. 2006; Zheng et al. 2015; Ahmed 2018). However, there is little information about optimal feed rations for juvenile pikeperch (Zakęś et al. 2003; Bódis and Bercsényi 2009; Kozłowski et al. 2018). Inappropriate amounts of feed provided for cultured species can lead to poor growth, malnutrition, size variation, increased aggression, and cannibalism (Dwyer et al. 2002; Fiogbé and Kestemont 2003; Kim et al. 2021). Moreover, excessive feed can lead to overloaded digestive systems, undesirable fat accumulation in tissues, and large increases in the quantity of excrement and unconsumed food that can deteriorate water quality (Du et al. 2006, Abbas and Siddiqui 2009, Mizanur and Bai 2014, Baloi et al. 2017). Feeds account for 30 to 70% of total production costs, depending on the species, and have a significant impact on the economic effectiveness of fish production (Gunther et al. 1992, Rad et al. 2003, Cho et al. 2006, Ahmed 2010, Luo et al. 2015, Zheng et al. 2015, Oyarzún et al. 2019, Hassan et al. 2021). Both underfeeding and overfeeding of cultured fishes cause stress and/or disease or mortality affecting the quality of the final product (López-Olmeda et al. 2012). Therefore, optimizing feeding rates is crucial to achieve the best growth results at the lowest possible production costs (Abbas and Siddiqui 2009, Desai and Singh 2009; Ahmed 2010; Okorie et al. 2013; Zheng et al. 2015, Kim et al. 2021).

Therefore, the aim of the study was to assess the effect of different feeding rates on growth parameters and to determine the optimal feed ration for juvenile pikeperch reared in three different size groups in a RAS (initial mean body weight 1.3, 9.4, and 25.6 g).

Materials and methods

Rearing conditions and experimental design

The study material was juvenile pikeperch obtained from artificial spawning (Zakęś 2013) and initial rearing at the Department of Sturgeon Breeding in Pieczarki of the National Inland Fisheries Research Institute in Olsztyn, Poland. Three separate experiments (I, II,

III) were conducted on fish of different initial body weights (1.3, 9.4, and 25.6 g). In experiment I (64 days post-hatch (DPH)), the average pikeperch body weight was 1.3 ± 0.0 g, and body length was 5.1 ± 0.1 cm. In experiment II (100 DPH), the body weight of pikeperch was 9.4 ± 0.2 g and its body length was 8.9 ± 0.0 cm. In experiment III (130 DPH), the body weight of pikeperch was 25.6 ± 0.2 g and its body length was 12.6 ± 0.1 cm (Table 1). Each group was conducted in triplicate. The fish were reared in 12 tanks with working volumes of 1.0 m^3 each (1.2 m × 1.2 m × 0.7 m). All experiments were performed in the same RAS with specification described in previous work (Kozłowski and Piotrowska 2023). The photoperiod applied during the experiments was 24 h light at an intensity of 4 lx. The stocking density of each of the experiments was determined based on a previous study (Kozłowski and Piotrowska 2023). In each part of the study, four experimental groups were reared to test the different feed rations, as follows:

- Experiment I: Group S3, feed ration 3.0% body weight (BW) day^{-1}; Group S3.5, feed ration 3.5% BW day^{-1}; Group S4, feed ration 4.0% BW day^{-1}; Group S4.5, feed ration 4.5% BW day^{-1};
- Experiment II: Group M2, feed ration 2.0% BW day^{-1}; Group M2.5, feed ration 2.5% BW day^{-1}; Group M3, feed ration 3.0% BW day^{-1}; Group M3.5, feed ration 3.5% BW day^{-1};
- Experiment III: Group L1, feed ration 1.0% BW day^{-1}; Group L1.5, feed ration 1.5% BW day^{-1}; Group L2, feed ration 2.0% BW day^{-1}; Group L2.5, feed ration 2.5% BW day^{-1}.

The pellet size of feed for different fish sizes in the three experiments was determined based on the results of a previous study (Kozłowski et al. 2021). The fish were fed commercial sinking feed manufactured by Aller Aqua (Denmark). Thalassa Ex GR 0.9–1.6 mm was used in experiment I; Thalassa Ex GR 1.3–2.0 mm was used in experiment II; and Thalassa Ex GR 1.6–2.4 mm was used in experiment III. All of the feeds contained 54% protein, 15% fat, and 8.5% carbohydrates. The feeds were delivered by automated band feeders (Fischtechnik GmbH, Germany) for 18 h day^{-1}.

Physical and chemical analyses of water

Water flow in the rearing tanks was maintained at a constant 12 l min^{-1}. Water temperature was measured daily and maintained at a constant level of 24 °C. Oxygen concentration

Table 1 Initial characteristics of pikeperch juveniles at the beginning of three separate experiments. Data of body weights and lengths are presented as mean ± SD

Experiment	Body weight (g)	Body length (cm)	Age (DPH)	Fish number per tank	Stocking density (kg m^{-3})
I	1.3 ± 0.0	5.1 ± 0.1	64	800	1.04
II	9.4 ± 0.2	8.9 ± 0.0	100	400	3.76
III	25.6 ± 0.2	12.6 ± 0.1	130	200	5.12

Abbreviations: *DPH* day post-hatch

at tank outflows was higher than 6.8 mg O_2 l^{-1}, and the water pH was 7.5–7.8. Measurements of these parameters were taken with a Cyber Scan 5500 (Eutech Instruments, USA). Total ammonia nitrogen ($TAN = NH_4^+\text{-N} + NH_3\text{-N}$) at the tank outflows did not exceed 0.30 mg l^{-1}, and the nitrite contents did not exceed 0.15 mg NO_2- l^{-1}. These parameters were determined with a Thermo Aquamate Plus UV–Vis spectrophotometer (Thermo Scientific, England).

Data collection and statistical analyses

The biomass and the number of fish in each tank were determined separately in each tank at the beginning and the end of each of the three experiments (I, II, and III). Additionally, on days 1, 7, 14, 21, and 28 of the experiments, body weight (BW), total length (TL), and body length (BL) were measured for 50 specimens from each tank to determine growth parameters and the weekly feed ration. Before the measurements, the fish were anesthetized with a solution of Propiscin (active ingredient etomidate) at a concentration of 0.8 ml l^{-1} water. Fish mortality was monitored and recorded daily. The following parameters were calculated from these data: specific growth rate: SGR (% d^{-1}) $= 100 \times (\ln BW_2 - \ln BW_1) \times T^{-1}$; feed conversion ratio, $FCR = TFC \times (FB - IB)^{-1}$; protein efficiency ratio $PER = (FB - IB) \times PI^{-1}$, feed efficiency FE (%) $= 100 \times (FB - IB)/TFC$; condition factor, $K = 100 \times BW \times BL^{-3}$, coefficient of variation for body weight, CV (%) $= 100 \times SD \times BW^{-1}$; survival, S (%) $= 100$ (FN IN^{-1}); weight gain WG (%) $= 100 \times (BW_2 - BW_1) \times {BW_1}^{-1}$; and biomass gain, BG (%) $= 100 \times (FB - IB) \times IB^{-1}$, where BW_1 is the initial body weight (g), BW_2 is the final body weight (g), BW is the body weight (g), T is the rearing period (days), BL is the body length (cm), SD is the body weight standard deviation, IB is the initial fish biomass (g), FB is the final fish biomass (g), IN is the initial number of fish (individuals), FN is the final number of fish (individuals), TFC is the total feed consumption (g), and PI is protein intake.

Mean values and standard deviations (SD) are presented. The normality of parameter distribution was tested by the Shapiro–Wilk test and, to confirm the homogeneity of variance, Levene's test. The data expressed in percentages were arcsin transformed before the statistical analysis. Data were compared using one-way ANOVA. The significance of differences was estimated using a post hoc HSD Tukey test ($P < 0.05$). Analyses were performed using STATISTICA 12 PL software (StatSoft, Poland). The optimum feed rate was determined by the specific growth rate (SGR) and weight gain (WG) using a second-order polynomial regression.

Results

The results of the study showed that in experiment I, the feed ration of 4.5% BW day^{-1} differed significantly from the feed ration of 3.5% BW day^{-1} for SGR and WG ($P < 0.05$). Feed efficiency and protein efficiency ratio decreased as feed ration increased from 3.0 to 4.5% BW day^{-1} (Table 2, $P < 0.05$). Survival was highest at feed rations from 4.5 to 3.5% BW day^{-1} and differed statistically from the feed ration of 3% BW day^{-1} ($P < 0.05$). The biomass gain achieved the highest value at a feed ration of 4.0–4.5% day^{-1} and differed statistically from groups S3 and S3.5 ($P < 0.05$).

In experiment II, the lowest final weight and the highest CV of pikeperch were achieved at the lowest feed ration of 2.0% BW day^{-1} which differed significantly from the other feed

Table 2 Growth parameters ($n = 3$ replicates) of pikeperch juveniles (initial body weight of 1.3 g) fed with different feed rations in experiment I (S3, 3.0% BW day^{-1}; S3.5, 3.5% BW day^{-1}; S4.0, 4% BW day^{-1}; S4.5, 4.5% BW day^{-1})

Parameter	Group S3	Group S3.5	Group S4	Group S4.5
Final weight (g)	6.9 ± 1.0^{a}	6.5 ± 0.5^{a}	6.8 ± 0.1^{a}	7.7 ± 0.5^{a}
Total length (TL, cm)	9.0 ± 0.5^{a}	9.2 ± 0.4^{a}	9.1 ± 0.2^{a}	9.5 ± 0.2^{a}
Body length (BL, cm)	7.9 ± 0.4^{a}	8.0 ± 0.2^{a}	7.8 ± 0.1^{a}	8.2 ± 0.2^{a}
Specific growth rate (SGR, % d^{-1})	5.80 ± 0.35^{ab}	5.66 ± 0.14^{b}	5.79 ± 0.10^{ab}	6.29 ± 0.23^{a}
Feed conversion ratio (FCR)	0.73 ± 0.03^{a}	0.75 ± 0.01^{a}	0.80 ± 0.06^{a}	0.79 ± 0.06^{a}
Protein efficiency ratio (PER)	2.53 ± 0.11^{a}	2.48 ± 0.04^{a}	2.31 ± 0.16^{a}	2.35 ± 0.18^{a}
Feed efficiency (FE, %)	136.5 ± 5.8^{a}	133.9 ± 2.3^{a}	124.7 ± 8.9^{a}	126.7 ± 9.5^{a}
Condition factor (K)	1.32 ± 0.01^{a}	1.32 ± 0.04^{a}	1.34 ± 0.07^{a}	1.33 ± 0.03^{a}
Body weight variation coefficient (CV, %)	38.7 ± 5.3^{a}	50.9 ± 0.8^{a}	54.7 ± 7.0^{a}	44.4 ± 8.7^{a}
Survival (S, %)	65.0 ± 2.7^{b}	75.4 ± 1.8^{a}	77.9 ± 2.5^{a}	79.2 ± 4.8^{a}
Weight gain (WG, %)	409.2 ± 51.9^{ab}	387.6 ± 18.8^{b}	406.3 ± 14.2^{ab}	482.4 ± 37.3^{a}
Biomass gain (BG, %)	330.1 ± 25.4^{b}	367.5 ± 13.0^{b}	394.0 ± 3.1^{a}	460.0 ± 12.6^{a}

All data are expressed as mean ± SD. Values marked with different letters show significant differences ($P < 0.05$) based on analysis of variance followed by using a post hoc HSD Tukey test

rations ($P < 0.05$). The lowest feed conversion ratio was recorded at the feed ration of 2.0% BW day^{-1}, which differed statistically from the feed rations of 3.0 and 3.5% BW day^{-1} ($P < 0.05$). Feed efficiency and PER decreased as feed rations increased from 2.0 to 3.5% BW day^{-1} (Table 3, $P < 0.05$).

In experiment III, the highest final weight, SGR, and WG were noted at the feed ration of 2.0 and 2.5% BW day^{-1}, which differed statistically from the other feed rations ($P < 0.05$). Total length, body length, and BG at feed rations of 2.0 and 2.5% BW day^{-1} were also

Table 3 Growth parameters ($n = 3$ replicates) of pikeperch juveniles (initial body weight of 9.4 g) fed with different feed rations in experiment II (M2, 2.0% BW day^{-1}; M2.5, 2.5% BW day^{-1}; M3, 3.0% BW day^{-1}; M3.5, 3.5% BW day^{-1})

Parameter	Group M2	Group M2.5	Group M3	Group M3.5
Final weight (g)	20.8 ± 1.7^{b}	23.4 ± 0.7^{a}	23.5 ± 0.8^{a}	23.8 ± 1.0^{a}
Total length (TL, cm)	14.2 ± 0.2^{a}	13.9 ± 0.3^{a}	14.6 ± 0.4^{a}	14.3 ± 0.2^{a}
Body length (BL, cm)	12.2 ± 0.1^{a}	12.0 ± 0.3^{a}	12.6 ± 0.4^{a}	12.4 ± 0.2^{a}
Specific growth rate (SGR, % d^{-1})	2.94 ± 0.30^{a}	3.22 ± 0.10^{a}	3.24 ± 0.15^{a}	3.26 ± 0.19^{a}
Feed conversion ratio (FCR)	0.70 ± 0.03^{a}	0.77 ± 0.03^{ab}	0.98 ± 0.17^{b}	1.28 ± 0.02^{c}
Protein efficiency ratio (PER)	2.64 ± 0.10^{a}	2.41 ± 0.10^{a}	1.93 ± 0.31^{b}	1.40 ± 0.12^{c}
Feed efficiency (FE, %)	142.6 ± 5.6^{a}	130.3 ± 5.6^{a}	104.5 ± 16.8^{b}	78.1 ± 4.2^{c}
Condition factor (K)	1.30 ± 0.02^{a}	1.35 ± 0.03^{a}	1.31 ± 0.01^{a}	1.33 ± 0.02^{a}
Body weight variation coefficient (CV, %)	44.5 ± 5.0^{b}	32.0 ± 2.3^{a}	32.3 ± 2.3^{a}	28.9 ± 5.8^{a}
Survival (S, %)	95.9 ± 3.3^{a}	96.8 ± 2.0^{a}	95.3 ± 5.1^{a}	87.6 ± 3.9^{a}
Weight gain (WG, %)	128.3 ± 19.0^{a}	146.5 ± 7.0^{a}	147.6 ± 10.5^{a}	149.5 ± 12.9^{a}
Biomass gain (BG, %)	218.6 ± 10.9^{a}	238.4 ± 2.7^{a}	236.4 ± 22.2^{a}	218.3 ± 6.6^{a}

All data are expressed as mean ± SD. Values marked with different letters show significant differences ($P < 0.05$) based on analysis of variance followed by using a post hoc HSD Tukey test statistically higher than those of fish fed with the feed ration of 1% BW day^{-1} ($P<0.05$). The feed conversion ratio was the lowest at a feed ration of 1.0 and 1.5% BW day^{-1} and differed statistically from group L2.5 ($P<0.05$). Feed efficiency and PER decreased as feed rations increased from 1.0 to 2.5% BW day^{-1} (Table 4, $P<0.05$). Statistically, the differences in condition factor between the feed ration of 1% BW day^{-1} and other feed rations were significant ($P<0.05$).

Statistical analysis (second-degree polynomial regression), based on SGR and WG, showed that the optimum feed ration for pikeperch was found at 2.35–2.39% BW day^{-1} only in experiment III ($P<0.05$, Fig. 1).

Discussion

In the present study, SGR values in all experiments increased with increasing levels of feeding. The highest SGR values were noted when the highest feed rations were applied (4.5%, 3.5%, and 2.5% BW day^{-1} in experiments I, II, and III, respectively), and these corresponded to the results of previous studies of pikeperch (Zakęś et al. 2003; Rónyai and Csengeri 2008; Kozłowski et al. 2018). The results of the present study were also consistent with those regarding other fish species, such as *Dicentrarchus labrax* (Linnaeus) (Eroldoğan et al. 2004), *Paralichthys olivaceus* (Temminck & Schlegel) (Cho et al. 2006), *Sebastes schlegeli* (Hilgendorf) (Mizanur and Bai 2014), *Sardinella brasiliensis* (Steindachner) (Baloi et al. 2017) , and *Siniperca scherzer* (Steindachner) (Kim et al. 2021).

The results of the current study showed that in all experiments, the lowest FCR values were noted with the lower feed rations, which is consistent with previous results observed in pikeperch reared in pond cages (Bódis and Bercsényi 2009). Studies conducted on *Cirrhinus mrigala* (Hamilton) (Khan et al. 2004), *Labeo rohita* (Hamilton) (Ahmed 2007), *Heteropneustes fossilis* (Bloch) (Ahmed 2010), *Oncorhynchus mykiss* (Walbaum) (Ahmed 2018), *Schizothorax zarudnyi* (Nikolskii) (Barani et al. 2019), *Eleginops maclovinus*

Table 4 Growth parameters ($n=3$ replicates) of pikeperch juveniles (initial body weight of 25.6 g) fed with different feed rations in experiment III (L1, 1.0% BW day^{-1}; L1.5, 1.5% BW day^{-1}; L2, 2.0% BW day^{-1}; L2.5, 2.5% BW day^{-1})

Parameter	Group L1	Group L1.5	Group L2	Group L2.5
Final weight (g)	36.5 ± 0.9^{c}	42.9 ± 1.1^{b}	47.8 ± 0.7^{a}	47.6 ± 0.4^{a}
Total length (TL, cm)	16.7 ± 0.2^{b}	17.3 ± 0.3^{a}	17.7 ± 0.1^{a}	17.7 ± 0.1^{a}
Body length (BL, cm)	14.5 ± 0.2^{b}	15.0 ± 0.2^{ab}	15.4 ± 0.1^{a}	15.4 ± 0.1^{a}
Specific growth rate (SGR, % d^{-1})	1.25 ± 0.10^{c}	1.87 ± 0.07^{b}	2.21 ± 0.12^{a}	2.26 ± 0.05^{a}
Feed conversion ratio (FCR)	0.81 ± 0.07^{a}	0.88 ± 0.10^{a}	0.96 ± 0.10^{ab}	1.21 ± 0.15^{b}
Protein efficiency ratio (PER)	2.31 ± 0.22^{a}	2.12 ± 0.25^{a}	1.94 ± 0.20^{ab}	1.54 ± 0.18^{b}
Feed efficiency (FE, %)	124.5 ± 12.1^{a}	114.2 ± 13.3^{a}	104.8 ± 10.6^{ab}	83.3 ± 9.8^{b}
Condition factor (K)	1.20 ± 0.01^{b}	1.29 ± 0.02^{a}	1.30 ± 0.01^{a}	1.30 ± 0.02^{a}
Body weight variation coefficient (CV, %)	29.7 ± 1.0^{a}	28.1 ± 2.1^{a}	27.8 ± 6.3^{a}	29.2 ± 7.3^{a}
Survival (S, %)	99.0 ± 1.3^{a}	94.8 ± 3.0^{a}	95.7 ± 2.5^{a}	94.7 ± 4.2^{a}
Weight gain (WG, %)	41.8 ± 3.9^{c}	68.9 ± 3.5^{b}	85.6 ± 6.4^{a}	88.2 ± 2.8^{a}
Biomass gain (BG, %)	140.3 ± 3.9^{b}	160.1 ± 8.4^{ab}	177.6 ± 8.5^{a}	178.2 ± 9.6^{a}

All data are expressed as mean ± SD. Values marked with different letters show significant differences ($P<0.05$) based on analysis of variance followed by using a post hoc HSD Tukey test

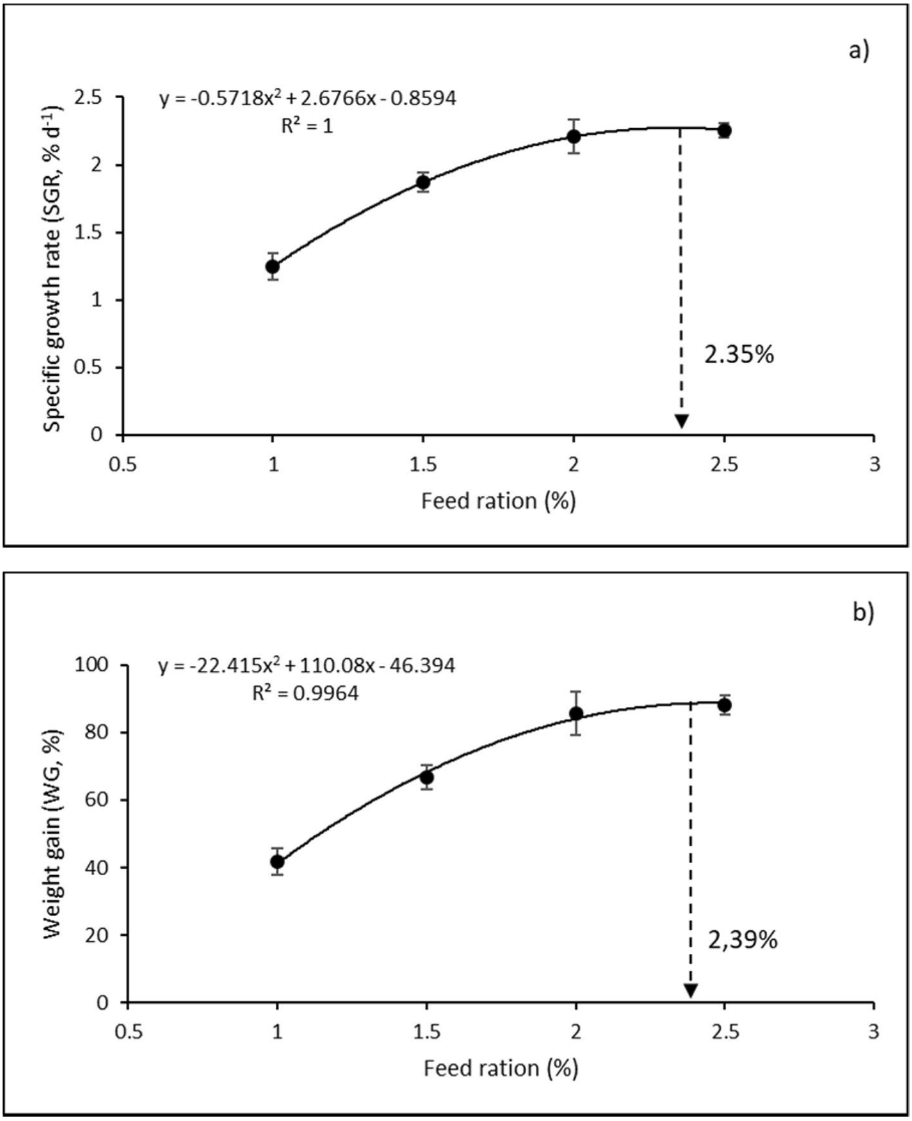

Fig. 1 Relationship between feed ration and specific growth rate (**a**) and weight gain (**b**). The optimum feed ration for juvenile pikeperch was estimated based on the second-order polynomial regression analysis in experimental III (initial body weight of 25.6 g, $n=3$)

(Cuvier) (Oyarzún et al. 2019), and *Lates calcarifer* (Bloch) (Hassan et al. 2021) showed that FCR values initially decreased and then increased with an increase in feed rations. At feed excess, the food passes through the digestive tract much more slowly, which impedes efficient digestion (Van Ham et al. 2003; Mizanur and Bai 2014; Baloi et al. 2017). Therefore, it is crucial to provide less feed than required for optimal feed ration while providing sufficient food for growth to reduce feed costs and water pollution (Dwyer et al. 2002; Cho et al. 2006).

The protein efficiency ratio (PER) of pikeperch fed different feed rations in the current study exhibited a decreasing trend with increasing feed rations. The maximum values were obtained with feed rations 3.0, 2.0, and 1.0% BW day^{-1} in experiments I, II, and III, respectively. These data are consistent with the results of studies of *Lutjanus argentimaculatus* (Forsskål) (Abbas and Siddiqui 2009) and *Cyprinus carpio* (Linnaeus) (Desai and Singh 2009). Other studies reported that PER values increased to a certain level of feeding but then decreased as feed rations were increased for *Cirrhinus mrigala* (Khan et al. 2004), *Heteropneustes fossilis* (Ahmed 2010), *Oncorhynchus mykiss* (Ahmed 2018), *Schizothorax zarudnyi* (Barani et al. 2019), *Lates calcarifer* (Hassan et al. 2021), and *Siniperca scherzeri* (Kim et al. 2021).

FE values always increase with increasing feed rations when the level of feeding is below the feed ration of fish. However, FE values decrease with increasing feed rations when the feeding level exceeds the optimal value for fish (Mihelakakis et al. 2002; Eroldoğan et al. 2004; Kim et al. 2021). In the current study, the highest FE was attained at the lowest feed rations (3, 2, and 1% BW day^{-1} in experiments I, II, and III, respectively), while this value decreased with increasing feed rations. Similar observations were reported for *Mystus nemurus* (Valenciennes) (Ng et al. 2000), *Ctenopharyngodon idella* (Valenciennes) (Du et al. 2006), *Cyprinus carpio* (Desai and Singh 2009), and *Paralichthys olivaceus* (Okorie et al. 2013). Probably, the minimal feed ration in the current study exceeded the living ration level for juvenile pikeperch that in groups S3, M2, and L1 still gained body weight at 409.2, 128.3, and 41.8%, respectively. Under restricted feeding conditions, fish growth decreases and FE values improve because fishes have the tendency to optimize digestion to better exploit the nutritional components of feed (Meyer-Burgdorff et al. 1989; Zoccarato et al. 1994; Van Ham et al. 2003).

The coefficient of body weight variation (CV) is used to identify changes in size that are caused by the effects of competition or hierarchy. CV values increase in fish populations in which the growth of some individuals is inhibited by the effects of competition or hierarchy (Jobling 1993, Jobling and Koskela 1996). In the current study, CV values did not differ significantly among the groups studied in experiment I, although the values of this parameter ranged from 38.7 to 54.7. The lack of a significant effect stemmed from the wide range of CV values among the replicates in each of the experiments, which is consistent with the results of Zakęś et al. (2003). In experiment II, the lowest feed ration (2% BW day^{-1}) caused an increase in CV values in this group compared to the groups in which smaller feed rations were applied. In experiment III, the CV values were stable in all the groups although the fish in the groups fed different feed rations exhibited significantly different growth. Similar results were obtained for *Sparus aurata* (Linnaeus) (Mihelakakis et al. 2002), *Limanda ferruginea* (Storer) (Puvanendran et al. 2003), *Scophthalmus maximus* (Linnaeus) (Van Ham et al. 2003), and pikeperch (Kozłowski et al. 2018).

The feed rations significantly influenced the survival of the pikeperch only in experiment I in which the smallest pikeperch individuals were used. The significantly lower survival of juvenile pikeperch fed the feed ration of 3% BW day^{-1} was likely caused by the occurrence of higher cannibalism in this group, evidence of which was the lowest CV value. This could be explained by the fact that in this group, the smallest fish were preyed upon most frequently. This is confirmed by the pikeperch in this group obtaining the same SGR value and final weight as the group in which the feed ration applied was 4% BW day^{-1}. Additionally, in all of the experiments, fish were observed to jump out of the tanks, which made it impossible to confirm cannibalism. This reaction was probably caused by the light intensity being too low. Every change in lighting and every time a staff member approached the tanks caused stress among the pikeperch, which resulted in fish losses. The presence of service staff near the tanks when the band feeder was delivering feed often caused feed losses because the pikeperch moved to the bottom of the tanks and ceased feeding. Steenfeldt et al. (2010) reported similar observations during pikeperch rearing.

Condition factor (CF) is used frequently to assess the nutritional status of fish since it is quick and easy to determine, and it provides information about the physiological state of fish (Ng et al. 2000, Eroldoğan et al. 2004, Abbas and Siddiqui 2009). In the current study, no significant differences in CF values were noted in experiments I or II. Similarly, no differences in CF were noted for *Dicentrarchus labrax* reared in both salt and fresh waters (Eroldoğan et al. 2004), *Paralichthys olivaceus* (Cho et al. 2006), and *Acipenser dabryanus* (Duméril) (He et al. 2023). In experiment III, no differences were noted among fish-fed feed rations of 1.5 to 2.5% BW day^{-1}, which suggests that pikeperch from these groups received appropriate nutrition. However, when feed ration 1.0% BW day^{-1} was applied, lower CF values were noted, which indicated that the ration was suboptimal. Zakęś et al. (2003) reported similar results for pikeperch with an initial body weight of approximately 25 g that were fed a feed ration of 1.2% BW day^{-1}. Lower CF values could have resulted from the utilization of the lipids in the intestines and the liver to meet energy and growth requirements (Du et al. 2006). Similar differences in fish condition indices fed suboptimal and optimal feed rations were noted for *Mystus nemurus* (Ng et al. 2000) and *Lutjanus argentimaculatus* (Abbas and Siddiqui 2009). In addition, increases in feed rations influenced CF values, which was consistent with previous reports on *Sparus aurata* (Mihelakakis et al. 2002), *Lates calcarifer* (Hassan et al. 2021), and *Siniperca scherzeri* (Kim et al. 2021).

The optimal feed ration for the maximum growth of fish differs depending on the fish species, size, and growth conditions (Mizanur and Bai 2014; Hassan et al. 2021; Kim et al. 2021). The optimal feed ration was determined based on second-degree polynomial regression analysis for SGR and WG and amounted to 2.35–2.39% BW day^{-1} for 25.6 g pikeperch. Recommended optimal feed rations for other fish species show a wide range of results obtained for similar groups of fish. For example, optimal feed rations for 2.6 g of *Dicentrarchus labrax* was 3.0–3.5% BW day^{-1} (Eroldoğan et al. 2004), for 27.1 g *Lutjanus argentimaculatus* was 2.5 BW day^{-1} (Abbas and Siddiqui 2009), for 3.1 g *Heteropneustes fossilis* was 4.0–4.5% BW day^{-1} (Ahmed 2010), for 5 and 20 g *Paralichthys olivaceus* was 5.1% and 3.4% BW day^{-1}, respectively (Okorie et al. 2013), for 5 and 16 g *Sebastes schlegeli* was 4.48–4.83% and 3.34–3.75 BW day^{-1}, respectively (Mizanur and Bai 2014), for 1.69 g *Sardinella brasiliensis* was 5.45 BW day^{-1} (Barani et al. 2019), for 1.42 g *Oncorhynchus mykiss* was 4.60–5.30% BW day^{-1} (Ahmed 2018), for 2.17 g *Schizothorax zarudnyi* was 4.9–5.2% BW day^{-1} (Barani et al. 2019), for 5.47 g *Lates calcarifer* was 6.5% BW day^{-1} (Hassan et al. 2021), and for 18.4 g *Siniperca scherzeri* was 1.88–2.80% BW day^{-1} (Kim et al. 2021).

Differences between the results of this study and those of others could stem from differences in fish size, experimental conditions, and methodology. Many factors affect fish growth, including feed composition, temperature, stocking density, feeding frequency, light intensity, and water quality (Ng et al. 2000; Fiogbé and Kestemont 2003; Eroldoğan et al. 2004; Ahmed 2018). Similarly to many other teleost fishes, the maximum pikeperch SGR values decreased as body weight increased from 6.29% day^{-1} (initial body weight of 1.3 g) to 2.26% day^{-1} (initial body weight of 25.6 g). This decrease in maximum growth rate associated with fish size was confirmed for *Perca fluviatilis* (Linnaeus) (Fiogbé and Kestemont 2003), *Paralichthys olivaceus* (Okorie et al. 2013), and *Acipenser medirostris* (Ayres) (Zheng et al. 2015). Since the current study only assessed feed rations, it remains to be determined whether optimizing other variables, such as temperature, feed composition, and frequency of feeding in combination with feed ration, could increase juvenile pikeperch growth. This is why the current experiment was conducted at a temperature (Rónyai and Csengeri 2008; Dalsgaard et al. 2013; Swirplies et al. 2019) and with a feed composition (Nyina-Wamwiza et al. 2005; Schulz et al. 2008) and a feeding frequency (Zakęś et al. 2006; Pěnka et al. 2023) that were determined to be optimal for this species. In the current experiment, these conditions were continuous feeding with a feed containing 54% protein, 15% fat, and 8.5% carbohydrates at a temperature of 24 °C.

To summarize, the results of the study indicated that under the same experimental conditions, the highest SGR values were noted with the highest feed rations. The lowest FCR occurred when the lowest feed ration was applied, while PER and FE values decreased with the increasing feed rations. One-way ANOVA of growth performance indicated that the optimum feeding rates could be 4.0–4.5, 2.5–3.5, and 2.0–2.5% BW day^{-1} for juvenile pikeperch with an initial body weight of 1.3, 9.4, and 25.6 g, respectively. A second-order polynomial regression based on SGR and WG indicated that the optimum feed ration for pikeperch of initial body weight was 2.35–2.39% BW day^{-1}. The results of this study provide important information for pikeperch farmers to achieve the best growth and feed efficiency, preventing water quality deterioration as a result of overfeeding and consequently reducing production costs.

Acknowledgements The study was conducted within the framework of the statutory research program of the National Inland Fisheries Research Institute in Olsztyn (No. Z-016).

Author contribution Conceptualization: Michał Kozłowski; methodology: Michał Kozłowski, Iwona Piotrowska; formal analysis and investigation: Michał Kozłowski, Iwona Piotrowska; writing—original draft preparation: Michał Kozłowski; writing—review and editing: Michał Kozłowski, Iwona Piotrowska; resources: Michał Kozłowski, Iwona Piotrowska; supervision: Michał Kozłowski. All the authors approved the final draft.

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethical approval The study was in compliance with Polish animal welfare regulations and approved by the Local Ethics Committee for Animal Experimentation of the National Inland Fisheries Research Institute in Olsztyn, Poland.

Competing interests The authors declare no competing interests.

References

Abbas G, Siddiqui PJA (2009) Effects of different feeding level on the growth, feed efficiency and body composition of juvenile mangrove red snapper, *Lutjanus argentimaculatus* (Forsskal 1775). Aquac Res 40(7):781–789. https://doi.org/10.1111/j.1365-2109.2008.02161.x

Ahmed I (2007) Effect of ration size on growth, body composition, and energy and protein maintenance requirement of fingerling Indian major carp, *Labeo rohita* (Hamilton). Fish Physiol Biochem 33(3):203–212. https://doi.org/10.1007/s10695-007-9132-y

Ahmed I (2010) Response to the ration levels on growth, body composition, energy, and protein maintenance requirement of the Indian catfish (*Heteropneustes fossilis*–Bloch 1974). Fish Physiol Biochem 36(4):1133–1143. https://doi.org/10.1007/s10695-010-9391-x

Ahmed I (2018) Effects of feeding levels on growth performance, feed utilization, body composition, energy and protein maintenance requirement of fingerling, rainbow trout, *Oncorhynchus mykiss* (Walbaum, 1792). Iran J Fish Sci 17(4):745–762. https://doi.org/10.22092/ijfs.2018.119209

Baloi MF, Sterzelecki FC, Sugai JK, Passini G, Carvalho CVA, Cerqueira VR (2017) Growth performance, body composition and metabolic response to feeding rates in juvenile Brazilian sardine *Sardinella brasiliensis*. Aquac Nutr 23(6):1458–1466. https://doi.org/10.1111/anu.12521

Barani H, Dahmardeh H, Miri M, Rigi M (2019) The effects of feeding rates on growth performance, conversion efficiency and body composition of juvenile snow trout *Schizothorax zarudnyi*. Iran J Fish Sci 18(3):507–516. https://doi.org/10.22092/IJFS.2019.118285

Bochert R (2022) Comparative performance, biochemical composition, and fatty acid analysis of Eurasian perch (*Perca fluviatilis*) during grow-out in RAS fed different commercial diets. J Appl Aquac 34(1):208–222. https://doi.org/10.1080/10454438.2020.1828217

Bódis M, Bercsényi M (2009) The effect of different daily feed rations on the growth, condition, survival and feed conversion of juvenile pikeperch (*Sander lucioperca*) reared with dry feed in net cages. Aquac Int 17(1):1–6. https://doi.org/10.1007/s10499-008-9226-2

Cho SH, Lee S-M, Park BH (2006) Effect of feeding ratio on growth and body composition of juvenile olive flounder *Paralichthys olivaceus* fed extruded pellets during the summer season. Aquaculture 251(1):78–84. https://doi.org/10.1016/j.aquaculture.2005.05.041

Dalsgaard J, Lund I, Thorarinsdottir R, Drengstig A, Arvonen K, Pedersen PB (2013) Farming different species in RAS in Nordic countries: current status and future perspectives. Aquac Eng 53:2–13. https://doi.org/10.1016/j.aquaeng.2012.11.008

Desai AS, Singh RK (2009) The effects of water temperature and ration size on growth and body composition of fry of common carp, *Cyprinus Carpio*. J Therm Biol 34(6):276–280. https://doi.org/10.1016/j.jtherbio.2009.03.005

Du ZY, Liu YJ, Tian LX, He JG, Cao JM, Liang GY (2006) The influence of feeding rate on growth, feed efficiency and body composition of juvenile grass carp (*Ctenopharyngodon idella*). Aquacult Int 14(3):247–257. https://doi.org/10.1007/s10499-005-9029-7

Dwyer KS, Brown JA, Parrish C, Lall SP (2002) Feeding frequency affects food consumption, feeding pattern and growth of juvenile yellowtail flounder (*Limanda ferruginea*). Aquaculture 213(1–4):279–292. https://doi.org/10.1016/S0044-8486(02)00224-7

Eroldoğan O, Kumlu M, Aktaş M (2004) Optimum feeding rates for European sea bass *Dicentrarchus labrax* L. reared in seawater and freshwater. Aquaculture 231(1–4):501–515. https://doi.org/10.1016/j.aquaculture.2003.10.020

FAO (2023) Sander lucioperca Linnaeus,1758. Fisheries and Aquaculture Division [online]. Rome. [Cited Thursday, May 11th 2023]. https://www.fao.org/fishery/en/aqspecies/3098/en

Fiogbé ED, Kestemont P (2003) Optimum daily ration for Eurasian perch *Perca fluviatilis* L. reared at its optimum growing temperatures. Aquaculture 216(1–4):243–252. https://doi.org/10.1016/S0044-8486(02)00409-X

Gunther J, Galvez-Hidalgo N, Ulloa-Rojas J, Coppoolse J, Verreth JAJ (1992) The effect of feeding level on growth and survival of jaguar guapote (*Cichlasoma managuense*) larval fed Artemia nauplii. Aquaculture 107(4):347–358. https://doi.org/10.1016/0044-8486(92)90082-V

Hassan UH, Mohammad AQ, Ahmad N, Masood Z, Hossain MY, Gabol K, Khan W, Hussain M, Ali A, Attaullah M, Kamal M (2021) Assessment of growth characteristics, the survival rate and body composition of Asian sea bass *Lates calcarifer* (Bloch, 1790) under different feeding rates in closed aquaculture system. Saudi J Biol Sci 28(2):1324–1330. https://doi.org/10.1016/j.sjbs.2020.11.056

He B, Zhou B, Xie H, Hu Z-T, Wang B, Zhang J-L, Li Q-Z, Zhao F-Q, Liu X, Li Q-D, Yan T (2023) Effect of feeding level on growth, digestive and metabolic enzymes and antioxidant capacity in juvenile Yangtze sturgeon (*Acipenser dabryanus*). Aquaculture 567:739265. https://doi.org/10.1016/j.aquaculture.2023.739265

Jankowska B, Zakeś Z, Zmijewski T, Szczepkowski M (2003) A comparison of selected quality features of the tissue and slaughter yield of wild and cultivated pikeperch *Sander lucioperca* (L.). Eur Food Res Technol 217:401–405. https://doi.org/10.1007/s00217-003-0757-5

Jobling M (1993) Bioenergetics: feed intake and energy partitioning. In: Rankin JC, Jensen FB (eds) Fish ecophysiology. Springer, Netherlands, pp 1–44. https://doi.org/10.1007/978-94-011-2304-4

Jobling M, Koskela J (1996) Interindividual variations in feeding and growth in rainbow trout during restricted feeding and in a subsequent period of compensatory growth. J Fish Biol 49(4):658–667. https://doi.org/10.1111/j.1095-8649.1996.tb00062.x

Kestemont P, Dabrowski K, Summerfelt RC (2015) Biology and culture of percid fishes: principles and practices. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-7227-3

Khan MA, Ahmed I, Abidi SF (2004) Effect of ration size on growth, conversion efficiency and body composition of fingerling mrigal, *Cirrhinus mrigala* (Hamilton). Aquac Nutr 10(1):47–53. https://doi.org/10.1046/j.1365-2095.2003.00279.x

Kim Y-O, Oh S-Y, Kim T (2021) Effects of the feeding rate on growth performance, body composition, and hematological properties of juvenile mandarin fish *Siniperca scherzeri* in a recirculating aquaculture system. Sustainability 13(15):8257. https://doi.org/10.3390/su13158257

Kottelat M, Freyhof J (2007) Handbook of European freshwater fishes. Kottelat, Cornol, Switzerland and Freyhof, Berlin, Germany, p 646

Kozłowski M, Szczepkowski M, Piotrowska I, Szczepkowska B (2018) Impact of feed ration on the growth and body weight variation in pikeperch (*Sander lucioperca*) at different life stages in a recirculating aquaculture system. Fish Aquat Life 26:201–210. https://doi.org/10.2478/aopf-2018-0022

Kozłowski M, Piotrowska I, Szczepkowska B (2021) Effect of feed pellet size and tank water level on growth performance in juvenile pikeperch, *Sander lucioperca* (L.), reared in a recirculating system. Fish Aquat Life 29(2):88–99. https://doi.org/10.2478/aopf-2021-0011

Kozłowski M, Piotrowska I (2023) Effect of stocking density on growth, survival and cannibalism of juvenile pikeperch, *Sander lucioperca* (L.), in a recirculating aquaculture system. Aquacult Int. https://doi.org/10.1007/s10499-023-01339-6

Liu Y, Liu H, Wua W, Yina J, Mouc Z, Hao F (2019) Effects of stocking density on growth performance and metabolism of juvenile Lenok (*Brachymystax lenok*). Aquaculture 504:107–113. https://doi.org/10.1016/j.aquaculture.2019.01.058

López-Olmeda JF, Noble C, Sánchez-Vázquez FJ (2012) Does feeding time affect fish welfare? Fish Physiol Biochem 38(1):143–152. https://doi.org/10.1007/s10695-011-9523-y

Luo L, Li T, Xing W, Xue M, Ma Z, Jiang N, Li W (2015) Effects of feeding rates and feeding frequency on the growth performances of juvenile hybrid sturgeon, *Acipenser schrenckii* Brandt♀ × *A. Baeri* Brandt♂. Aquaculture 448:229–233. https://doi.org/10.1016/J.AQUACULTURE.2015.06.005

Meyer-Burgdorff KH, Osman MF, Gunther KD (1989) Energy metabolism in *Oreochromis niloticus*. Aquaculture 79(1–4):283–291. https://doi.org/10.1016/0044-8486(89)90469-9

Mihelakakis A, Tsolkas C, Yoshimatsu T (2002) Optimization of feeding rate for hatchery-produced juvenile gilthead sea bream *Sparus aurata*. J World Aquac Soc 33(2):169–175. https://doi.org/10.1111/j.1749-7345.2002.tb00491.x

Mizanur RM, Bai SC (2014) The optimum feeding frequency in growing Korean rockfish (*Sebastes schlegeli*) rearing at the temperature of 15 °C and 19 °C. Asian-Australas J Anim Sci 27(9):1319–1327. https://doi.org/10.5713/ajas.2014.14193

Ng W-K, Lu K-S, Hashim R, Ali A (2000) Effects of feeding rate on growth, feed utilization and body composition of a tropical bagrid catfish. Aquacult Int 8(1):19–29. https://doi.org/10.1023/A:1009216831360

Nyina-Wamwiza L, Xu XL, Blanchard G, Kestemont P (2005) Effect of dietary protein, lipid and carbohydrate ratio on growth, feed efficiency and body composition of pikeperch *Sander lucioperca* fingerlings. Aquac Res 36(5):486–492. https://doi.org/10.1111/j.1365-2109.2005.01233.x

Okorie OE, Bae JY, Kim KW, Son MH, Kim JW, Bai SC (2013) Optimum feeding rates in juvenile olive flounder, *Paralichthys olivaceus*, at the optimum rearing temperature. Aquac Nutr 19(3):267–277. https://doi.org/10.1111/j.1365-2095.2012.00956.x

Oyarzún R, Martínez D, Soto-Dávila M, Muñoz JLP, Dantagnan P, Vargas-Chacoff L (2019) Effect of ration level on growth performance, body composition, intermediary metabolism and serum parameters in juvenile Patagonian blennie *Eleginops maclovinus*. Comp Biochem Physiol Part A Mol Integr Physiol 230:122–130. https://doi.org/10.1016/j.cbpa.2019.01.013

Pěnka T, Malinovskyi O, Imentai A, Kolářová J, Kuĉera V, Policar T (2023) Evaluation of different feeding frequencies in RAS-based juvenile pikeperch (*Sander lucioperca*) aquaculture. Aquaculture 562:738815. https://doi.org/10.1016/j.aquaculture.2022.738815

Policar T, Schaefer FJ, Panana E, Meyer S, Teerlinck S, Toner D, Żarski D (2019) Recent progress in European percid fish culture production technology-tackling bottlenecks. Aquacult Int 27(5):1151–1174. https://doi.org/10.1007/s10499-019-00433-y

Puvanendran V, Boyce D, Brown J (2003) Food ration requirements of 0+ yellowtail flounder *Limanda ferruginea* (Storer) juveniles. Aquaculture 220(1–4):459–475. https://doi.org/10.1016/S0044-8486(02)00620-8

Rad F, Köksal G, Kindir M (2003) Growth performance and food conversion ratio of Siberian sturgeon (*Acipenser baeri* Brandt) at different daily feeding rates. Turk J Vet Anim Sci 27(5):1085–1090

Rónyai A, Csengeri I (2008) Effect of feeding regime and temperature on ongrowing results of pikeperch (*Sander lucioperca* L.). Aquac Res 39(8):820–827. https://doi.org/10.1111/j.1365-2109.2008.01935.x

Schulz C, Huber M, Ogunji J, Rennert B (2008) Effects of varying dietary protein to lipid ratios on growth performance and body composition of juvenile pike perch (*Sander lucioperca*). Aquac Nutr 14(2):166–173. https://doi.org/10.1111/j.1365-2095.2007.00516.x

Steenfeldt SJ, Vestergaard M, Overton JL, Lund I, Paulsen H, Larsen VJ, Henriksen NH (2010) Videreudvikling af intensivt opdræt af sandart i Danmark. DTU Aqua. DTU Aqua-rapport Nr. 228–2010

Sunde LM, Imsland AK, Folkvord A, Stefansson SO (1998) Effects of size grading on growth and survival of juvenile turbot at two temperatures. Aquacult Int 6(1):19–32. https://doi.org/10.1023/A:1009265602388

Swirplies F, Wuertz S, Baßmann B, Orban A, Schäfer N, Brunner RM, Hadlich F, Goldammer T, Rebl A (2019) Identification of molecular stress indicators in pikeperch *Sander lucioperca* correlating with rising water temperatures. Aquaculture 501:260–271. https://doi.org/10.1016/j.aquaculture.2018.11.043

Tönißen K, Pfuhl R, Franz GP, Dannenberger D, Bochert R, Grunow B (2022) Impact of spawning season on fillet quality of wild pikeperch (*Sander lucioperca*). Eur Food Res Technol 248:1277–1285. https://doi.org/10.1007/s00217-022-03963-7

Van Ham EH, Berntssen MH, Imsland AK, Parpoura AC, Bonga SEW, Stefansson SO (2003) The influence of temperature and ration on growth, feed conversion, body composition and nutrient retention of juvenile turbot (*Scophthalmus maximus*). Aquaculture 217(1–4):547–558. https://doi.org/10.1016/S0044-8486(02)00411-8

Zakęś Z (2013) Out-of-season spawning of cultured pikeperch [Sander lucioperca (L.)]. Aquac Res 38(13):1419–1427. https://doi.org/10.1111/j.1365-2109.2007.01831.x

Zakęś Z, Szkudlarek M, Woźniak M, Demska-Zakęś K, Czerniak S (2003) Effects of feeding regimes on growth, within-group weight variability, and chemical composition of the juvenile zander, *Sander lucipoperca* (L.) body. EJPAU 6 (1) #4. http://www.ejpau.media.pl/volume6/issue1/fisheries/art-04.html

Zakęś Z, Kowalska A, Czerniak S, Demska-Zakęś K (2006) Effect of feeding frequency on growth and size variation in juvenile pikeperch, *Sander lucioperca* (L.). Czech J Anim Sci 51(2):85–91. https://doi.org/10.17221/3914-CJAS

Zheng K, Deng D, De Riu N, Moniello G, Hung S (2015) The effect of feeding rate on the growth performance of green sturgeon (*Acipenser medirostris*) fry. Aquac Nutr 221(4):489–495. https://doi.org/10.1111/anu.12179

Zoccarato I, Benatti G, Bianchini ML, Boccignone M, Conti A, Napolitano R, Palmegiano GB (1994) Differences in performance, flesh composition and water output quality in relation to density and feeding levels in rainbow trout, *Oncorhynchus mykiss* (Walbaum), farming. Aquac Res 25(6):639–647. https://doi.org/10.1111/j.1365-2109.1994.tb00728.x