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IMPACT OF INTENSIVE AND SEMI-INTENSIVE FARMING ON HISTOLOGICAL FEATURES AND CULINARY PROPERTIES OF COMMON CARP (*CYPRINUS CARPIO* L.) FILLETS

– Research paper –

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Abstract: Eco-intensification of freshwater aquaculture production is considered one of the solutions to achieve global food security. However, intensification of the production may come with product quality trade-offs, which are unlikely to be accepted by modern consumers. The aim of this study was to evaluate impact of intensive cage farming and typical semi-intensive pond culture on culinary and histological characteristics of common carp (*Cyprinus carpio* L.) fillets. In intensive cage culture common carp were fed formulated feed for 60 days, while in semi-intensive pond farming fish utilised natural food and supplementary grains (triticale) for 90 days to achieve similar weight. Next, fish were sacrificed, filleted and quality of fillets, i.e. pH, colour, histology of muscle tissue, texture and sensory properties were assessed. The results showed that intensive cage culture, because of constant water flow, contributed to muscle development through hypertrophy mechanism and resulted with higher number of large muscle fibers (over 60 µm in diameter) compared to semi-intensive pond farming. The differences in histology of muscle tissue were correlated with sensory characteristics of fillets, but not with texture instrumental analysis. Appearance (colour) and taste of the fillets of common carp from semi-intensive pond farming was more attractive from consumers' perspective, especially that no negative features, such as off-flavour were noted compared to intensive cage culture.

Key words: freshwater aquaculture, intensive cage culture, muscle histology, semi-intensive pond farming, quality trade-offs

INTRODUCTION

Blue foods or seafood, considered as a production of marine and freshwater organisms in diverse farming systems, are key animal protein sources and thus exert huge impact on the food security on a global scale. Considering specific features of different farming regions, the overall annual aquaculture production steadily grows on a global scale and in 2020 reached 88 mln t (FAO 2020). Further growth of aquaculture production is mainly possible considering all three pillars of the sustainable production, and this approach applies to all farmed species, farming systems and interrelated sectors (e.g. agriculture) (Little et al. 2018, Pounds et al. 2022). An important part of European fish farming is the freshwater aquaculture with common carp (*Cyprinus carpio* L.) as one of the main species that clearly supports livelihoods, economies, and cultures. Production of common carp in EU was 96 800 tons in 2022 and cultivation is typically extensive or semi-intensive, and takes place in earthen ponds (FAO 2024). These systems are considered as relatively environmentally friendly, since ponds prevent local areas from floods and provide habitat for numerous flora and fauna species, whose life cycle is highly dependent on access to lentic waters (Kestemont 1995). Individuals reach a market size of 1.5 – 2 kg in a three-year period and peak season for common carp sales and consumption mainly occur during Christmas period. To meet the consumer needs common carp is offered on the market in various forms, including whole live fish, carcass, and increasingly popular fillets. However, to overcome seasonal interest in common carp consumption numerous attempts are made to increase consumer's interest throughout the whole year, e.g. through delivering deskinned, deboned, or restructured carp products. A good example might be a Carp Ham

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produced in Poland (Skałecki et al. 2016) or carp sausages available on the market in Czech Republic (Kašpar and Buchtova 2015). However, to ensure high quality of common carp products, it is of utmost importance to assess the influence of nutrition on the quality properties (muscle histology, texture, sensory features) of common carp fillets. Especially when new intensive fish farming systems (e.g. cages) are under development, natural food is no longer the main food source and is replaced by formulated feeds (Sobczak et al. 2020).

Changes in quality properties of fillets resulting from combined effect of various farming methods and dietary treatments have been described for numerous fish species but only partially for common carp. For example, Másílko et al. (2015) compared filet quality properties of common carp cultured in extensive culture system (lower stocking density with no supplemental feeding) and a semi-intensive system (supplementary feeding with cereals). Outcomes of the trial showed that supplementary feeding resulted in higher fat content and lower hardness of common carp filets. Moreover, authors underlined that the quality of common carp fillets primary depend on the applied farming system, i.e. feeding strategies and general pond management. Farming of common carp has been tested also in cage culture systems and possibilities to profile culinary and technological properties of common carp fillets proved. Sobczak et al. (2020) reported possibility to modify nutritional value and sensory properties of meat of common carp cultured in cage system and fed with diets enriched with algae meal and salmon oil. Fillets of carp fed diet enriched with algae meal and salmon oil extracted from by-products had a higher level of protein, lower level of fat, and energy value comparing to control. The trials revealed that quality parameters of common carp fillets show high level of phenotypic plasticity in relation to farming system. However, information on the differences between fillet quality of common carp farmed in different systems are fragmented and scarce, especially in relation to market size common carp that must meet the expected consumer demands. Therefore, the aim of the present study was to evaluate impact of intensive cage farming and typical semi-intensive pond culture on selected culinary and technological quality parameters of common carp meat.

MATERIALS AND METHODS

Fish trials and sampling

The intensive common carp rearing trial was performed at the Fisheries Research Station (FRS), Nowe Czarnowo, Poland (N: 53°120′ 36″ E: 14° 270′ 48″), in the floating set of cages (n = 3), with net volume 3 m^3, submerged in the cooling water discharged from the Dolna Odra Power Plant, with water flow 24–32 m^3/s. One week prior to start of the experiment 300 carps of 427 ± 10 g mean initial body weight were randomly selected from common carp semi-intensive pond farm located in Maliniec, Poland (N: 53° 42′ 31″ E: 15° 21′ 42″) during fish translocation, transported to the FRS facility, and randomly distributed in cages for acclimatisation (100 fish/cage). The 60-day fish trial (May – July) was performed in triplicate, using Aller Classic feed (Table 1) manufactured through extrusion process.

The fish were fed the experimental diet to apparent satiation three times a day (at 10:00, 14:00 and 18:00 hours, in equal portions). This ration was approx. 3% of live weight per day. During the trial water temperature oscillated between 18°C at the beginning of the experiment and 28°C in the final days of the trial.

Table 1. Feed formulation fed to common carp during intensive cage culture.

Component	Amount
Analytical constituents	
Crude protein (%)	30.0
Crude fat (%)	7.0
NFE (%)	44.3
Fibre (%)	4.4
Ash (%)	6.3
P (%)	1.0
Na (%)	0.2
Ca (%)	0.9
Nutritional	
Vitamin A (IU/ kg)	10 000
Vitamin D3 (IU/ kg)	2 000
I* (mg/ kg)	3.0
Cu* (mg/ kg)	5.0
Mn* (mg/ kg)	12.0
Zn* (mg/ kg)	100.0
Antioxidant	
BHT (ppm)	70.0
BHA (ppm)	45.0

Abbreviations: NFE – Nitrogen-free extract; BHT - Butylated hydroxytoluene (E321); BHA - Butylated hydroxyanisole (E320); I (Ca iodate anhydrous 3b202); Cu (Cu sulphate pentahydrate); Mn (Mn sulphate monohydrate 3b503); Zn (Zn sulphate monohydrate 3b604).

A month later after the intensive cage farming trial end, fish from Maliniec semi-intensive pond farm (11 ha production pond) were collected as part of standard farm screening (90-day trial). Samples were collected with delay to achieve comparable fish weight in both systems. Common carp in semi-intensive ponds utilised mainly natural food and were supplementary fed with triticale. Water temperature in the production pond during that period was between 8°C and 20.2°C. At the end of experimental trial 9 (n = 3 per cage) fish and 9 fish from Maliniec semi-intensive pond farm were randomly selected, weighed (PS 6000/C/1, Radwag), and sacrificed using a lethal dose of the anaesthetic (2-phenoxyethanol, Sigma-Aldrich). Next, fish were filleted, fillets were weighed (PS 6000/C/1, Radwag) and fillet yield (Fy) was calculated by using Equation 1:

$$Fy = \frac{FW}{FBW} \times 100\% \quad (1)$$

where: FBW – fish body weight (g); FW – fillets weight (g).

Subsequently, fragments of raw muscle samples for histological assessment were collected from the dorsal part of fillets (approx. 5 x 5 x 10 mm) of three randomly selected fish from each group and fixed for 12 hours in Sannomiya solution. Additionally, fillets from three randomly selected fish from each group were collected, stored on ice and transferred to laboratory for further analysis.

Assessment of fillets physicochemical properties

Proximate composition of fillets was assessed according to Association of Official Analytical Chemists (AOAC, 2007). Briefly, dry matter was obtained after drying samples to a constant weight in laboratory dryer at 105°C for 24 hrs, while ash content was determined after incineration in a muffle furnace at 550°C for 6 hrs. Crude protein was measured by determining nitrogen content (N x 6.25), according to the Kjeldahl method, using a Tecator Kjeltec 2100 distillation unit (FOSS Analytical Co., Ltd.), whereas crude lipid was determined gravimetrically, after Soxhlet lipid extraction on a Tecator Soxtec System HT 1043 (FOSS Analytical Co., Ltd.). The colour features of fillets were measured by the colorimeter 3nh NR20XE (3nh). The colour parameters measured were lightness (L*), red/green colour contribution (a*), and blue/yellow colour contribution (b*), whereas whiteness index (WI), total chromaticity (C), and colour tone (h) indices were calculated from the values obtained for L*, a* and b* by using Equations 2–4:

$$WI = 100 - [(100 - L)^2 + a^2 + b^2]^{0.5} \quad (2)$$

$$C = (a^2 + b^2)^{0.5} \quad (3)$$

$$h = \operatorname{atan}\frac{b}{a} \quad (4)$$

The pH of the fillets was measured using an ELMETRON CP-411 pH meter (Elmetron). Next, fillets were weighted using electronic balance PS 6000/C/1 (Radwag), steamed up to 68°C at their centre, cooled down to 20 °C and weighed again to calculate cooking losses by using Equation 5:

$$\text{Cooking loss } (\%) = \frac{FWb - Fwa}{FWb} \times 100 \quad (5)$$

where: FWb – fillet weight before thermal treatment (g); FWa – fillet weight after thermal treatment (g).

Muscle histological assessment

Fragments of raw muscle fixed for 12 hours in Sannomiya solution, were subsequently dehydrated in absolute ethanol, saturated in intermediate solutions (benzene, 1:1 v/v benzene:paraffin), and embedded in paraffin blocks. The blocks were then sectioned into 10 ± 1 μm slices with a microtome (HM 310, Microm International). The sections were mounted on glass slides, contrast-stained with haematoxylin and eosin, and sealed with Canada balsam (Burck, 1975). Muscle fiber cross-sectional area (A), *endomysium* and *perimysium* thickness were recorded using Nikon Eclipse E600 microscope and NIS-Elements Basic Research software (Nikon Instruments Europe BV). Three glass slides from each group were screened and for each parameter a minimum of 200 measurements were performed. Cross-section area (A) was used to calculate fiber diameter (D) by following Equation 6 (Alami-Durante et al. 1997):

$$D = 2A^{0.5}\pi^{-0.5} \quad (6)$$

Next, fiber diameters were distributed into seven size classes (< 20 μm, 20–40 μm, 40–60 μm, 60–80 μm, 80–100 μm, 100-120 μm, > 120 μm) following Weatherley et al. (1988).

Fillet texture and sensory analysis

The texture profile and sensory analysis of fillets were determined based on steamed and cooled down samples (details above). Texture measurements were performed on 1 cm x 1 cm x 1.5 cm blocks cut from fillets of 15 mm height in 5 replicates for each group using TA.XT Plus Texture Analyser (Stable Micro Systems). Texture parameters (hardness, cohesiveness, springiness, plasticity, chewiness, gumminess) were determined, using TPA compressive strength test with 50 mm/min traverse speed and deformation level of 80% (Bourne, 1982). The sensory evaluation of the common carp tissues was conducted by a panel of five trained experts with, in general, a minimum 5 years of experience in texture analysis of fish, meat and meat products. Analysis

included texture properties: springiness, hardness, tenderness, cohesiveness, wateriness, juiciness, chewiness, connective tissue perceptibility and fattiness, as well as appearance: colour evenness, cross-section structure and gapping, odour and taste intensity: boiled meat, fish, feed and other (channel/geosmin taste). All parameters were assessed using a 5-point scale, where 1 responds to the lowest intensity and 5 to highest intensity of feature (PN-ISO 11036:1999).

Statistical analysis

All statistical analyses were performed using Statistica 13 software (StatSoft, Inc.). The normality of data distribution was assessed by the Shapiro–Wilk test. Significance of the observed differences between samples were assessed using paired t-test. In sensory analysis when no variance was observed in a sample parameter one sample t-test was performed against value. Differences were considered statistically significant at $P \leq 0.05$. Corelation matrix was created to link histological features of common carp muscle with instrumental and sensory texture, as well as colour parameters of the fish fillets.

RESULTS

Assessment of fillets physicochemical properties

The final body weight of common carp from the intensive cage culture and semi-intensive earthen ponds during sampling were comparable (953.12 ± 158.24 g and 1024.26 ± 118.96 g, respectively). The fillet yield was significantly ($P \leq 0.05$) higher for common carp from intensive cage farming (58 ± 4%) compared to fish from semi-intensive pond farming (50 ± 12%), despite no difference in fillets weight (553.07 ± 102.1 g and 499.70 ± 116.92 g, respectively). Common carp fillets proximate composition differed between farming systems (Table 2).

Fillets of common carp from cage farming had higher crude protein content and higher dry matter content, when compared to semi-intensive pond culture. The pH value was lower in fillets of common carp cultured in cages than in fillets of carp from ponds (Table 3). Significantly different values of pH did not significantly affect cooking losses. Higher contributions of red and yellow colour were found in fillets from common carp farmed in semi-intensive pond system. Moreover, chromaticity was approx. 3 times lower in fillets of common carp reared in intensive cage culture.

Table 2. Proximate composition of fillets from common carp reared in intensive cage farming and in semi-intensive pond culture.

Component	Cage culture	Pond farming
Crude protein (%)	$17.97^{b} \pm 0.34$	$16.38^{a} \pm 0.14$
Crude fat (%)	3.95 ± 1.30	3.16 ± 0.13
Dry matter (%)	$23.24^{b} \pm 1.37$	$20.75^{a} \pm 0.14$
Ash (%)	1.08 ± 0.03	1.07 ± 0.01

Values represent mean value ± standard deviation. Values in rows with different superscripts are significantly different ($P \leq 0.05$).

Histological analysis

Histological examination of muscle tissues showed differences in size distribution of muscle fiber diameters in five out of seven classes between common carp from intensive cage culture and semi-intensive pond farming (Figure 1). Muscle of common carp from pond farming showed significantly ($P \leq 0.05$) higher share of small muscle fibers (classes < 20 μm and 40-60 μm), while muscle of common carp from cage culture had higher share of large muscle fibers (classes 60-80 μm, 80-100 μm and 100-120 μm). Additionally, thicker *endomysium* was found in common carp from semi-intensive system (2.31 ± 0.01 μm), compared to common carp from cage culture (2.10 ± 0.49 μm) (Figure 2). No differences were found in *perimysium* thickness.

Table 3. The colour parameters, pH, and cooking loss yield of fillets from common carp reared in intensive cage farming and in semi-intensive pond culture.

Parameter	Cage culture	Pond farming
pH	$6.59^{a} \pm 0.26$	$6.91^{b} \pm 0.14$
L*	45.25 ± 2.51	48.54 ± 4.05
a*	$9.40^{a} \pm 1.98$	$31.35^{b} \pm 4.13$
b*	$4.12^{a} \pm 1.02$	$13.10^{b} \pm 3.01$
WI	44.27 ± 2.83	37.92 ± 5.39
C	$10.27^{a} \pm 2.17$	$34.23^{b} \pm 4.57$
h	0.41 ± 0.05	0.41 ± 0.04
Cooking loss (%)	16.34 ± 3.65	16.07 ± 1.53

Explanations: L* – colour brightness; a* – red colour contribution; b* – yellow colour contribution; WI – blind (whiteness) index; C – chromaticity; h – colour tone. Values in rows with various superscripts are significantly different ($P \leq 0.05$). Values represent mean value ± standard deviation.

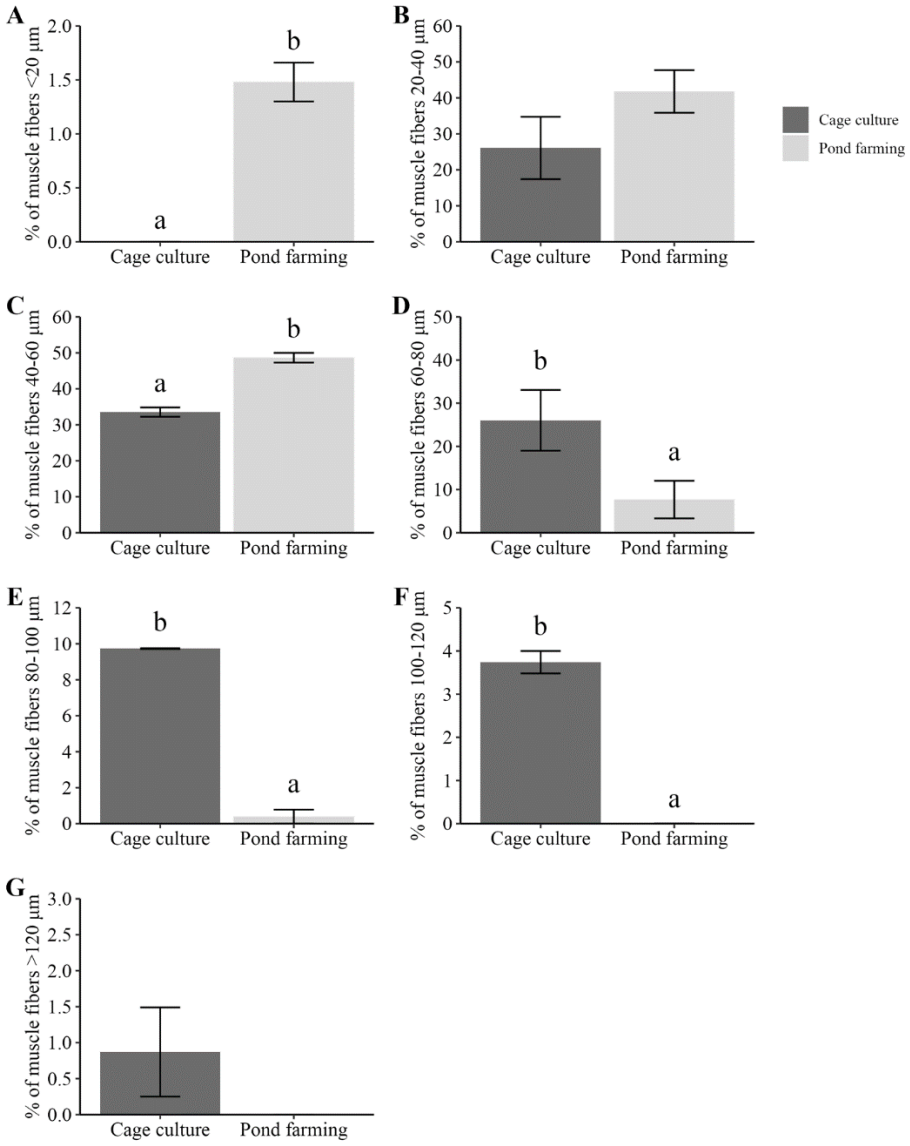

Figure 1. Differences in distribution of muscle fiber sizes between fillets of common carp from intensive cage production and semi-intensive pond culture. Values presented as mean ± standard deviation, different letters indicate significant differences ($P \leq 0.05$). A – share of muscle fibers with diameter < 20 µm; B – share of muscle fibers with diameter between 20 µm and 40 µm; C – share of muscle fibers with diameter between 40 µm and 60 µm; D – share of muscle fibers with diameter between 60 µm and 80 µm; E – share of muscle fibers with diameter between 80 µm and 100 µm; F – share of muscle fibers with diameter between 100 µm and 120 µm; G – share of muscle fibers with diameter >120 µm.

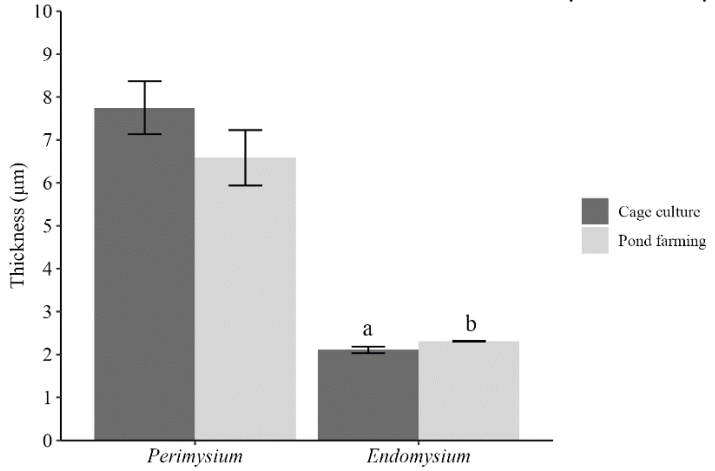

Figure 2. *Perimysium* and *endomysium* thickness in fillets of common carp from intensive cage culture and semi-intensive pond farming. Values are presented as mean ± standard deviation, different letters indicate significant differences ($P \leq 0.05$).

Fillets texture and sensory properties

No significant differences ($P > 0.05$) were found in instrumentally measured texture between fillets of common carp from intensive cage farming and fillets of fish from semi-intensive pond culture (Table 4). However, significant ($P \leq 0.05$) differences between texture of the fillets were identified by sensory evaluation in all parameters except juiciness, fattiness, and perceptibility of connective tissue (Table 5). Fillets of common carp from semi-intensive pond culture showed more springiness, cohesiveness and hardness, while fillets from intensive cage culture were more tender, watery and chewy compared to semi-intensive culture common carp fillets. Furthermore, sensory evaluation revealed undesirable aspects of intensive cage culture, such as geosmin and feed off-flavours.

Correlation of histological features with texture and colour of the fillets

Correlation matrix revealed 141 significant correlations between histological, texture and colour parameters, among which 73 were positively correlated and 68 negatively correlated (Tables 6-9). Out of all correlations found, the most interesting were the strong correlation of the share of small muscle fibers (classes > 20 μm, 20-40 μm, and 40-60 μm) with sensory hardness (R^2 = 0.97, 0.88, and 0.94 respectively) and negative correlation with sensory chewiness (R^2 = -0.97, -0.93, and -0.88 respectively). Contrary, the large muscle fibers (classes 60–80 μm, 80-100 μm, 100-120 μm, and > 120 μm) were inversely correlated with sensory hardness (R^2 = -0.95, -0.97, -0.95, and -0.90 respectively) and corelated with sensory chewiness (R^2 = 0.97, 0.95, 0.92 and 0.82 respectively). Additionally, endomysium thickness was positively correlated with small muscle fiber classes (R^2 between 0.86 and 0.94) and inversely correlated with large muscle fiber classes (R^2 between -0.88 and -0.98). The colour L*, a*, and b* parameters were positively correlated with small muscle fibers (classes < 20 μm and 40–60 μm; R^2 between 0.85 and 0.99), except class 20–40 μm and inversely correlated with large muscle fibers (classes 60–80 μm, 80-100 μm, and 100-120 μm; R^2 between -0.88 and -0.99), except L* and 60–80 μm class (R^2 = -0.79).

Table 4. Texture parameters of filets of common carp from intensive cage farming and semi-intensive pond culture obtained with TPA test with deformation level of 80%.

Parameter	Cage culture	Pond farming
Hardness (N)	1.80 ± 0.29	1.77 ± 0.18
Cohesiveness	0.15 ± 0.03	0.16 ± 0.05
Springiness (cm)	0.44 ± 0.16	0.51 ± 0.25
Plasticity (cm)	0.76 ± 0.16	0.69 ± 0.25
Chewiness (N×cm)	0.12 ± 0.06	0.12 ± 0.08
Gumminess (N)	0.24 ± 0.10	0.30 ± 0.13

Values represent mean ± standard deviation.

Table 5. Sensory attributes of cooked filets of common carp from intensive cage farming and semi-intensive pond culture.

Attribute group	Attribute	Cage culture	Pond farming
Appearance	Colour evenness	3.88 ± 0.38	3.75 ± 0.42
	Cross section structure	3.88 ± 0.38	3.75 ± 0.42
	Gaping	1.00 ± 0.00	1.00 ± 0.00
Texture	Springiness	1.50^a ± 0.35	2.13^b ± 0.54
	Cohesiveness	1.38^a ± 0.21	2.38^b ± 0.38
	Hardness	1.63^a ± 0.21	2.25^b ± 0.22
	Tenderness	3.13^b ± 0.80	1.75^a ± 0.27
	Wateriness	2.25^b ± 0.27	1.75^a ± 0.22
	Juiciness	2.63 ± 0.70	2.25 ± 0.27
	Perceptibility of connective tissue	1.25 ± 0.22	1.38 ± 0.38
	Chewiness	2.13^b ± 0.38	1.25^a ± 0.27
	Fattiness	2.25 ± 0.27	1.88 ± 0.21
Odour intensity	Boiled meat	1.00 ± 0.00	1.00 ± 0.00
	Fish	1.50 ± 0.00	1.50 ± 0.00
	Feed	1.88^b ± 0.95	1.00^a ± 0.00
Taste intensity	Boiled meat	1.00 ± 0.00	1.13 ± 0.21
	Fish	1.38 ± 0.38	1.63 ± 0.21
	Feed	2.25^b ± 0.22	1.00^a ± 0.00
	Channel (geosmin)	2.38^b ± 0.21	1.00^a ± 0.00

Values in rows with different superscripts are significantly different ($P \leq 0.05$). Values represent mean ± standard deviation.

Table 6. Correlations between histological parameters

	Variable	muscle fibers with diameter <20 µm	muscle fibers with diameter 20–40 µm	muscle fibers with diameter 40–60 µm	muscle fibers with diameter 60–80 µm	muscle fibers with diameter 80-100 µm	muscle fibers with diameter 100–120 µm	muscle fibers with diameter >120 µm	perimysium thickncess (µm)	endomysium thickness (µm)
Histological parameters	muscle fibers with diameter <20 µm	1.000000	0.830975	0.967119	-0.911630	-0.996206	-0.987673	-0.764900	-0.807269	0.909179
	muscle fibers with diameter 20–40 µm	0.830975	1.000000	0.699386	-0.984067	-0.805900	-0.748956	-0.931727	-0.988981	0.939938
	muscle fibers with diameter 40–60 µm	0.967119	0.699386	1.000000	-0.814946	-0.984175	-0.994616	-0.702350	-0.648484	0.860461
	muscle fibers with diameter 60–80 µm	-0.911630	-0.984067	-0.814946	1.000000	0.896462	0.852810	0.934326	0.960665	-0.977915
	muscle fibers with diameter 80-100 µm	-0.996206	-0.805900	-0.984175	0.896462	1.000000	0.995887	0.769171	0.770362	-0.912215
	muscle fibers with diameter 100–120 µm	-0.987673	-0.748956	-0.994616	0.852810	0.995887	1.000000	0.718948	0.710613	-0.877528
	muscle fibers with diameter >120 µm	-0.764900	-0.931727	-0.702350	0.934326	0.769171	0.718948	1.000000	0.869039	-0.963301
	perimysium thickncess (µm)	-0.807269	-0.988981	-0.648484	0.960665	0.770362	0.710613	0.869039	1.000000	-0.886845
	endomysium thickness (µm)	0.909179	0.939938	0.860461	-0.977915	-0.912215	-0.877528	-0.963301	-0.886845	1.000000
Instrumental texture	Hardness (N)	0.355049	0.073327	0.336555	-0.134886	-0.332613	-0.360065	0.112576	-0.127785	0.071204
	Cohesiveness	0.471993	0.698320	0.266798	-0.626197	-0.409454	-0.350560	-0.471280	-0.769074	0.484704
	Springiness (cm)	0.691357	0.735690	0.577938	-0.736416	-0.660895	-0.626694	-0.606277	-0.754658	0.671308
	Plasticity (cm)	-0.691357	-0.735690	-0.577938	0.736416	0.660895	0.626694	0.606277	0.754658	-0.671308
	Chewiness (N×cm)	-0.404499	-0.180511	-0.431721	0.250977	0.408613	0.429465	0.135379	0.176649	-0.257572
	Gumminess	0.723214	0.460329	0.641761	-0.522199	-0.683013	-0.692753	-0.196922	-0.528287	0.419741
Sensory texture	Springiness	0.689425	0.245689	0.849675	-0.412633	-0.742793	-0.794286	-0.367639	-0.158562	0.538336
	Cohesiveness	0.951675	0.655516	0.998203	-0.779021	-0.972199	-0.987944	-0.666500	-0.601837	0.831854
	Hardness	0.965406	0.884810	0.942693	-0.952521	-0.972528	-0.953354	-0.895221	-0.833003	0.980953
	Tenderness	-0.992236	-0.789609	-0.952915	0.872995	0.982613	0.978586	0.686604	0.780753	-0.854261
	Wateriness	-0.858072	-0.937754	-0.808659	0.964451	0.863503	0.823481	0.986380	0.877511	-0.993951
	Juiciness	-0.640095	-0.958483	-0.467103	0.893092	0.603736	0.529029	0.880402	0.962248	-0.824120
	Perceptibility of connective tissue	0.750855	0.778931	0.571003	-0.764473	-0.690560	-0.652577	-0.505386	-0.852735	0.624148
	Chewiness	-0.971448	-0.927510	-0.882182	0.968162	0.951657	0.922916	0.822663	0.922099	-0.930257
	Fattiness	-0.790422	-0.994895	-0.663764	0.972329	0.769448	0.709093	0.955987	0.974425	-0.939500
Colour parameters	L*	0.845351	0.698454	0.896336	-0.792888	-0.877378	-0.875782	-0.806164	-0.612672	0.879667
	a*	0.994050	0.810548	0.949386	-0.889282	-0.983614	-0.976522	-0.709249	-0.801123	0.869341
	b*	0.993268	0.772982	0.980912	-0.868000	-0.994407	-0.994543	-0.715205	-0.745719	0.875714
	WI	-0.807315	-0.683640	-0.686579	0.716101	0.762775	0.748057	0.440067	0.741047	-0.609874
	C	0.995293	0.804994	0.956348	-0.886745	-0.986917	-0.981103	-0.711369	-0.792353	0.871735
	h	0.180399	-0.192708	0.412398	0.046490	-0.259277	-0.320794	-0.068676	0.310428	0.139376

Table 7. Correlations between textural instrumental parameters

	Variable	Hardness (N)	Cohesiveness	Springiness (cm)	Plasticity (cm)	Chewiness (N×cm)	Gumminess
Histological parameters	muscle fibers with diameter <20 µm	0.355049	0.471993	0.691357	-0.691357	-0.404499	0.723214
	muscle fibers with diameter 20–40 µm	0.073327	0.698320	0.735690	-0.735690	-0.180511	0.460329
	muscle fibers with diameter 40–60 µm	0.336555	0.266798	0.577938	-0.577938	-0.431721	0.641761
	muscle fibers with diameter 60–80 µm	-0.134886	-0.626197	-0.736416	0.736416	0.250977	-0.522199
	muscle fibers with diameter 80-100 µm	-0.332613	-0.409454	-0.660895	0.660895	0.408613	-0.683013
	muscle fibers with diameter 100–120 µm	-0.360065	-0.350560	-0.626694	0.626694	0.429465	-0.692753
	muscle fibers with diameter >120 µm	0.112576	-0.471280	-0.606277	0.606277	0.135379	-0.196922
	perimysium thicknccss (µm)	-0.127785	-0.769074	-0.754658	0.754658	0.176649	-0.528287
	endomysium thickness (µm)	0.071204	0.484704	0.671308	-0.671308	-0.257572	0.419741
Instrumental texture	Hardness (N)	1.000000	0.133871	-0.205738	0.205738	-0.111523	0.784085
	Cohesiveness	0.133871	1.000000	0.605413	-0.605413	0.294354	0.477557
	Springiness (cm)	-0.205738	0.605413	1.000000	-1.000000	-0.431286	0.437193
	Plasticity (cm)	0.205738	-0.605413	-1.000000	1.000000	0.431286	-0.437193
	Chewiness (N×cm)	-0.111523	0.294354	-0.431286	0.431286	1.000000	-0.387731
	Gumminess	0.784085	0.477557	0.437193	-0.437193	-0.387731	1.000000
Sensory texture	Springiness	0.278716	-0.211079	0.216747	-0.216747	-0.414121	0.388934
	Cohesiveness	0.345910	0.220956	0.547795	-0.547795	-0.440000	0.635164
	Hardness	0.181957	0.429423	0.665086	-0.665086	-0.334134	0.529662
	Tenderness	-0.428218	-0.487849	-0.690527	0.690527	0.426351	-0.799082
	Wateriness	0.006683	-0.467638	-0.643174	0.643174	0.212132	-0.324671
	Juiciness	0.055640	-0.748144	-0.674843	0.674843	0.047733	-0.298315
	Perceptibility of connective tissue	0.439508	0.809170	0.726559	-0.726559	-0.267261	0.838548
	Chewiness	-0.305113	-0.626682	-0.754942	0.754942	0.339249	-0.707655
	Fattiness	-0.001950	-0.668715	-0.706259	0.706259	0.144399	-0.370973
Colour parameters	L*	-0.044875	0.083696	0.622230	-0.622230	-0.538588	0.308541
	a*	0.434370	0.503475	0.679693	-0.679693	-0.405460	0.793325
	b*	0.425688	0.415695	0.616321	-0.616321	-0.391774	0.743776
	WI	-0.663112	-0.729597	-0.539070	0.539070	0.149954	-0.928866
	C	0.433538	0.488526	0.669126	-0.669126	-0.403341	0.785540
	h	0.133343	-0.553747	-0.360482	0.360482	-0.001175	-0.110390

Table 8. Correlations between sensorial parameters

	Variable	Springiness	Cohesivenes s	Hardness	Tenderness	Wateriness	Juiciness	Perceptibility of connective tissue	Chewiness	Fattiness
Histological parameters	muscle fibers with diameter <20 µm	0.689425	0.951675	0.965406	-0.992236	-0.858072	-0.640095	0.750855	-0.971448	-0.790422
	muscle fibers with diameter 20–40 µm	0.245689	0.655516	0.884810	-0.789609	-0.937754	-0.958483	0.778931	-0.927510	-0.994895
	muscle fibers with diameter 40–60 µm	0.849675	0.998203	0.942693	-0.952915	-0.808659	-0.467103	0.571003	-0.882182	-0.663764
	muscle fibers with diameter 60–80 µm	-0.412633	-0.779021	-0.952521	0.872995	0.964451	0.893092	-0.764473	0.968162	0.972329
	muscle fibers with diameter 80-100 µm	-0.742793	-0.972199	-0.972528	0.982613	0.863503	0.603736	-0.690560	0.951657	0.769448
	muscle fibers with diameter 100–120 µm	-0.794286	-0.987944	-0.953354	0.978586	0.823481	0.529029	-0.652577	0.922916	0.709093
	muscle fibers with diameter >120 µm	-0.367639	-0.666500	-0.895221	0.686604	0.986380	0.880402	-0.505386	0.822663	0.955987
	perimysium thicknccss (µm)	-0.158562	-0.601837	-0.833003	0.780753	0.877511	0.962248	-0.852735	0.922099	0.974425
	endomysium thickness (µm)	0.538336	0.831854	0.980953	-0.854261	-0.993951	-0.824120	0.624148	-0.930257	-0.939500
Instrumental texture	Hardness (N)	0.278716	0.345910	0.181957	-0.428218	0.006683	0.055640	0.439508	-0.305113	-0.001950
	Cohesiveness	-0.211079	0.220956	0.429423	-0.487849	-0.467638	-0.748144	0.809170	-0.626682	-0.668715
	Springiness (cm)	0.216747	0.547795	0.665086	-0.690527	-0.643174	-0.674843	0.726559	-0.754942	-0.706259
	Plasticity (cm)	-0.216747	-0.547795	-0.665086	0.690527	0.643174	0.674843	-0.726559	0.754942	0.706259
	Chewiness (N×cm)	-0.414121	-0.440000	-0.334134	0.426351	0.212132	0.047733	-0.267261	0.339249	0.144399
	Gumminess	0.388934	0.635164	0.529662	-0.799082	-0.324671	-0.298315	0.838548	-0.707655	-0.370973
Sensory texture	Springiness	1.000000	0.878438	0.668897	-0.675593	-0.488046	0.029951	0.100617	-0.501260	-0.220038
	Cohesiveness	0.878438	1.000000	0.922846	-0.939418	-0.777817	-0.413690	0.534522	-0.853594	-0.618853
	Hardness	0.668897	0.922846	1.000000	-0.925578	-0.956325	-0.721519	0.637865	-0.948975	-0.869788
	Tenderness	-0.675593	-0.939418	-0.925578	1.000000	0.792013	0.592140	-0.791836	0.960835	0.737882
	Wateriness	-0.488046	-0.777817	-0.956325	0.792013	1.000000	0.843816	-0.566947	0.889897	0.948122
	Juiciness	0.029951	-0.413690	-0.721519	0.592140	0.843816	1.000000	-0.722914	0.792263	0.968255
	Perceptibility of connective tissue	0.100617	0.534522	0.637865	-0.791836	-0.566947	-0.722914	1.000000	-0.848185	-0.716713
	Chewiness	-0.501260	-0.853594	-0.948975	0.960835	0.889897	0.792263	-0.848185	1.000000	0.891702
	Fattiness	-0.220038	-0.618853	-0.869788	0.737882	0.948122	0.968255	-0.716713	0.891702	1.000000
Colour parameters	L*	0.777471	0.890709	0.911591	-0.790881	-0.865276	-0.514018	0.363011	-0.775624	-0.698467
	a*	0.659405	0.934027	0.934089	-0.998819	-0.810008	-0.619733	0.798531	-0.969430	-0.761108
	b*	0.746701	0.971068	0.948229	-0.989813	-0.819135	-0.562822	0.710328	-0.943039	-0.729046
	WI	-0.322016	-0.664673	-0.670713	0.855745	0.536225	0.559401	-0.925679	0.840346	0.611841
	C	0.675934	0.941952	0.937947	-0.998584	-0.812823	-0.610464	0.783831	-0.966064	-0.756480
	h	0.787881	0.455088	0.235494	-0.141139	-0.131970	0.390886	-0.462851	0.027553	0.176835

Table 9. Correlations between colour parameters

	Variable	L*	a*	b*	WI	C	h
Histological parameters	muscle fibers with diameter <20 µm	0.845351	0.994050	0.993268	-0.807315	0.995293	0.180399
	muscle fibers with diameter 20–40 µm	0.698454	0.810548	0.772982	-0.683640	0.804994	-0.192708
	muscle fibers with diameter 40–60 µm	0.896336	0.949386	0.980912	-0.686579	0.956348	0.412398
	muscle fibers with diameter 60–80 µm	-0.792888	-0.889282	-0.868000	0.716101	-0.886745	0.046490
	muscle fibers with diameter 80-100 µm	-0.877378	-0.983614	-0.994407	0.762775	-0.986917	-0.259277
	muscle fibers with diameter 100–120 µm	-0.875782	-0.976522	-0.994543	0.748057	-0.981103	-0.320794
	muscle fibers with diameter >120 µm	-0.806164	-0.709249	-0.715205	0.440067	-0.711369	-0.068676
	perimysium thickncess (µm)	-0.612672	-0.801123	-0.745719	0.741047	-0.792353	0.310428
	endomysium thickness (µm)	0.879667	0.869341	0.875714	-0.609874	0.871735	0.139376
Instrumental texture	Hardness (N)	-0.044875	0.434370	0.425688	-0.663112	0.433538	0.133343
	Cohesiveness	0.083696	0.503475	0.415695	-0.729597	0.488526	-0.553747
	Springiness (cm)	0.622230	0.679693	0.616321	-0.539070	0.669126	-0.360482
	Plasticity (cm)	-0.622230	-0.679693	-0.616321	0.539070	-0.669126	0.360482
	Chewiness (N×cm)	-0.538588	-0.405460	-0.391774	0.149954	-0.403341	-0.001175
	Gumminess	0.308541	0.793325	0.743776	-0.928866	0.785540	-0.110390
Sensory texture	Springiness	0.777471	0.659405	0.746701	-0.322016	0.675934	0.787881
	Cohesiveness	0.890709	0.934027	0.971068	-0.664673	0.941952	0.455088
	Hardness	0.911591	0.934089	0.948229	-0.670713	0.937947	0.235494
	Tenderness	-0.790881	-0.998819	-0.989813	0.855745	-0.998584	-0.141139
	Wateriness	-0.865276	-0.810008	-0.819135	0.536225	-0.812823	-0.131970
	Juiciness	-0.514018	-0.619733	-0.562822	0.559401	-0.610464	0.390886
	Perceptibility of connective tissue	0.363011	0.798531	0.710328	-0.925679	0.783831	-0.462851
	Chewiness	-0.775624	-0.969430	-0.943039	0.840346	-0.966064	0.027553
	Fattiness	-0.698467	-0.761108	-0.729046	0.611841	-0.756480	0.176835
Colour parameters	L*	1.000000	0.788396	0.830441	-0.368723	0.796965	0.398459
	a*	0.788396	1.000000	0.990528	-0.861311	0.999695	0.133362
	b*	0.830441	0.990528	1.000000	-0.808199	0.993615	0.266230
	WI	-0.368723	-0.861311	-0.808199	1.000000	-0.853049	0.164626
	C	0.796965	0.999695	0.993615	-0.853049	1.000000	0.157425
	h	0.398459	0.133362	0.266230	0.164626	0.157425	1.000000

DISCUSSION

Sustainable aquaculture intensification is one of the solutions to assure food security worldwide with indisputable role of freshwater aquaculture – a major contributor of seafood supply chain (Zhang et al. 2022). To increase self-sufficiency, European freshwater aquaculture should take advantage of available farming opportunities, in which fish can be farmed more intensively (e.g. power plant or waste incineration plant cooling waters, cage farming) due to increased water temperature, which is stimulating fish growth (Panicz et al. 2022). However, as our results indicate intensification of common carp farming through cage culture and use of formulated feed comes with some fish fillets quality trade-offs.

The advantages of faster growth of fish in intensive farming systems and the resulting more efficient feed utilization are undeniable. Comparably, in semi-intensive pond farming, common carp reached a similar size in an additional 30 days. Higher fillet yield noted in common carp from intensive cage farming also suggest more efficient feed use, and consequently resulted in higher protein content in the fillets compared to common carp from semi-intensive pond culture. Our results are in line with Marković et al. (2016), who suggested increased protein content in common carp muscle when fish were fed formulated feeds. However, Marković et al. (2016) also suggested increased intermuscular fat content in common carp fed artificial diet, which was not the case in our study. This could be a result of specific conditions during the trial as cages were placed in the discharge channel of running post-cooling water from power plant. In these conditions fish had to actively swim against the current and possibly utilised energy resources from the feed to maintain position and navigate in the cage (Rasmussen et al. 2013). Whereas, in semi-intensive pond farming there is limited or no water flow. Different swimming behaviour possibly may have also influenced muscle development of carps farmed in the intensive and semi-intensive systems. In common carp from intensive cage culture muscle hypertrophy was observed, since our study showed higher number of large diameter (over 60 μm) muscle fiber compared to fish from semi-intensive pond culture. Similar results were reported for farmed Atlantic cod (*Gadus morhua* L.) subjected to sustained exercise, where increased waterflow resulted with increased muscle fibers diameter (Bjørnevik et al. 2003). Enhanced exercise training also caused hypertrophic muscle growth in hapuku wreckfish (*Polyprion oxygeneios*) exposed to increased water currency (Khan 2015). However, environmental factors such as water temperature or oxygen level can also cause muscle hypertropia in fish, suggesting a combined effect of different factors affecting fillets structure of common carp from intensive cage culture (Kiessling et al. 2006).

The difference in muscle fibre distribution between common carp from intensive cage culture and semi-intensive pond farming did not influence texture parameters of fillets measured with texture analyser. In this context, our findings are in contrast with previously reported in Hurling et al. (1996) relationship between fiber diameter and fillet firmness. However, sensory analysis reviled differences in texture parameters (springiness, cohesiveness, hardness, tenderness, wateriness and chewiness) between carp from intensive cage culture and semi-intensive pond farming, among which hardness and chewiness were strongly correlated with muscle fiber distribution. Connective tissue thickness also influences the texture of fish fillets (Kiessling et al. 2006). Our study found that *endomysium* had lower thickness in common carp from intensive cage culture compared to fish from semi-intensive farming, yet no differences in organoleptic perceptibility of connective tissue were found. The results of sensory analysis and histological analysis are in line with Mørkøre et al. (2009), in which multifactorial character of Atlantic salmon (*Salmo salar*) meat texture was reported. Furthermore, our results indicate that sensory tests are equally important as instrumental analysis to assure attractive quality of fish products for consumers (Aussanasuwannakul et al. 2010). Although, in some cases instrumental analysis was more sensitive to detect changes in fillets texture compared to sensory analysis (Bland et al. 2018).

Fillets colour, among other factors, is considered one of the most important features for seafood consumers, mainly because it reflects fish quality and freshness before consumers' purchase decision (Viana et al. 2022). Colour of the fillets is directly linked with fillet chemical composition, muscle fibre size, and density of the muscle fibres (Haard 1992, Johnston et al. 2000, Rincón et al. 2016). In this study we found major differences in red and yellow colours contribution between common carp fillets collected from two farming systems, suggesting a varied fillets quality between semi-intensive system and intensive cage culture particularly linked with feeding strategy. The red colour of the fillets is often considered more attractive by consumers, not only for obvious species like Atlantic salmon or rainbow trout

(*Oncorhynchus mykiss*) but also in freshwater species (Beg et al. 2023), thus in our case, fillets of common carp from semi-intensive pond culture should be considered as more likely preferred by consumers compared to fillets of common carp from intensive cage culture. Moreover, lightness (L*) of common carp fillets, often linked with amount of free water in the meat (Jørpeland et al. 2015), was comparable in intensive and semi-intensive culture. Further, cooking loss of both variants did not differ, confirming similar free water content, despite slight difference in pH value, suggesting similar suitability for processing.

One of the key findings of our research was the appearance of off-flavours in the fillets of common carp from intensive cage culture, which are unacceptable and disqualifying for consumers (Drake et al. 2010). We assume that off-flavours are resultant of farming conditions, not processing processes, therefore, the solution to eliminate off-flavours and make the product suitable for consumers could be depuration and starvation in running water (Lv et al. 2018). Otherwise, if off-flavours are appealing post-processing, innovative removal strategies can be harnessed (Zhou et al. 2023).

In conclusion, our study shows differences between two common carp production systems, i.e. intensive cage culture and semi-intensive pond farming. Both systems have their advantages, disadvantages, and limitations (Table 10), thus further studies should focus on combining advantages of them, to achieve better self-sufficiency and food security in the future. In addition, redesigning of production system is needed to produce more attractive, sustainable and high-quality products for consumers.

Table 10. Advantages and disadvantages of intensive cage culture and semi-intensive pond farming.

Advantages	Disadvantages
Cage culture	
More control over the feeding	Off-flavour appearance
Faster growth	Higher costs
Higher fillets yield	
Pond farming	
Less resources used for production	Weather dependent growth
More appealing product	Higher mortality rate
Better texture of the fillets	

CONCLUSIONS

The study provides insights on the impact of semi-intensive pond farming and intensive cage culture on physiological responses as well as technological and culinary features of common carp meat. Here, we revealed direct impact of the farming type on the histological parameters of muscle tissue as well as between meat properties and sensory attributes of common carp meat. Fish farmed in the cages submerged in the cooling channel were fed pelleted feed that increased total protein level in fillets. Additionally, farming in a lotic condition of the cooling channel affected histological parameters of carp muscles (increased diameter of muscle fiber, thinner *endomysium*) that have eventually translated to compromised culinary parameters (e.g. cohesiveness) of the common carp meat. On the other hand, common carp farmed in traditional conditions in which fish utilised natural food base and were not exposed to significant currents, thus sustained normal development of skeletal muscles and assured high-quality of meat for common carp consumers. Our results indicate that there is possibility to shape sensory properties of muscles to meet market expectations towards common carp meat. Moreover, nutritional and quality trade-offs should be eliminated in future by reasonable combining traditional semi-intensive farming with modern and efficient intensive cage culture.

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REFERENCES

1. Alami-Durante, H., Fauconneau, B., Rouel, M., Escaffre, A.M. & Bergot P. (1997). Growth and multiplication of white skeletal muscle fibres in carp larvae in relation to somatic growth rate. *J Fish Biol.* 50**,** 1285–1302DOI: 10.1111/j.1095-8649.1997.tb01653.x.
2. AOAC. (2007). *Official methods of analysis of AOAC International*. Gaithersburg: MD, AOAC International.
3. Aussanasuwannakul, A., Kenney, P.B., Brannan, R.G., Slider, S.D., Salem, M. & Yao J. (2010). Relating instrumental texture, determined by variable-blade and Allo-Kramer shear attachments, to sensory analysis of rainbow trout, *Oncorhynchus mykiss*, fillets. *J Food Sci.* 75(7), S365–S374. DOI:10.1111/j.1750-3841.2010.01770.x.
4. Beg, M.M., Roy, S.M., Moulick, S. & Mandal, B. (2023). Quality evaluation of organically farmed fish fillet of Indian major carps. *Aquac. Int*. 31(5), 2743–2761. DOI: 10.1007/s10499-023-01107-6.
5. Bjørnevik, M., Karlsen, Ø., Johnston, I.A. & Kiessling, A. (2003). Effect of sustained exercise on white muscle structure and flesh quality in farmed cod (*Gadus morhua* L.). *Aquac. Res*. 34(1), 55–64. DOI: 10.1046/j.1365-2109.2003.00794.x.
6. Bland, J.M., Bett-Garber, K.L., Li, C.H., Brashear, S.S., Lea, J.M. & Bechtel P.J. (2018). Comparison of sensory and instrumental methods for the analysis of texture of cooked individually quick frozen and fresh-frozen catfish fillets. *Food Sci. Nutr*., 6(6), 1692–1705. DOI: 10.1002/fsn3.737.
7. Bourne, M. (1982). *Food Texture and Viscosity: Concept and Measurement*. San Diego, California: Academic Press.
8. Burck, H.C. (1975). *Utrwalanie. Technika histologiczna***.** Warszawa: PZWL - Państwowy Zakład Wydawnictw Lekarskich.
9. Drake, S.L., Drake, M.A., Sanderson, R., Daniels, H.V. & Yates, M.D. (2010). The effect of purging time on the sensory properties of aquacultured southern flounder (*Paralichthys lethostigma*). *J. Sens. Stud.* 25(2), 246–259. DOI: 10.1111/j.1745-459X.2009.00255.x.
10. FAO. (2020). *The State of World Fisheries and Aquaculture 2020. Sustainability in action.* Rome. DOI: 10.4060/ca9229en.
11. FAO. (2024). *Fishery and Aquaculture Statistics. Global aquaculture production 1950-2022 (FishStatJ).* www.fao.org/fishery/en/statistics/software/fishstatj
12. Haard, N.F. (1992). Biochemistry and chemistry of color and color change in seafoods. *Adv. Seafood Biochem.* 305–360.
13. Hurling, R., Rodell, J.B. & Hunt, H.D. (1996). Fiber diameter and fish texture. *J. Texture Stud.* 27(6), 679–685. DOI: 10.1111/j.1745-4603.1996.tb01001.x.
14. Johnston, I.A., Alderson, R., Sandham, C., Dingwall, A., Mitchell, D., Selkirk, C., Nickell, D., Baker, R., Robertson, B., Whyte, D. & Springate, J. (2000). Muscle fibre density in relation to the colour and texture of smoked Atlantic salmon (*Salmo salar* L.). *Aquaculture* 189(3-4), 335–349. DOI: 10.1016/S0044-8486(00)00373-2.
15. Jørpeland, G., Imsland, A., Stien. L.H., Bleie, H. & Roth, B. (2015). Effects of filleting method, stress, storage and season on the quality of farmed Atlantic cod (*Gadus morhua* L.). *Aquacult. Res.* 46(7), 1597–1607. DOI: 10.1111/are.12312.
16. Kašpar, L. & Buchtova, H. (2015). Sensory evaluation of sausages with various proportions of *Cyprinus carpio* meat. *Czech J. Food Sci*. 33(1), 45-51. DOI: 10.17221/293/2014-CJFS.
17. Kestemont, P. (1995). Different systems of carp production and their impacts on the environment. *Aquaculture* 129, 347–372. DOI: 10.1016/0044-8486(94)00292-V.
18. Khan, J.R., Pether, S., Bruce, M., Walker, S. P., Hemar, Y. & Herbert, N.A. (2015). Exercise training reduces the flesh firmness of juvenile hāpuku (*Polyprion oxygeneios*) with a hypertrophic reduction in muscle fibre density. *N. Z. J. Mar. Freshw. Res*. 49(4), 429–438. DOI: 10.1080/00288330.2015.1069362.
19. Kiessling, A., Ruohonen, K. & Bjørnevik, M. (2006). Muscle fibre growth and quality in fish. *Arch. Tierz., Dummerstorf* 49, 137–146.
20. Little, D.C., Young, J.A., Zhang, W., Newton, R., Al Mamun, A. & Murray, F.J. (2018). Sustainable intensification of aquaculture value chains between Asia and Europe: A framework for understanding impacts and challenges. *Aquaculture* 493, 338–354. DOI: 10.1016/j.aquaculture.2017.12.033.
21. Lv, H., Hu, W., Xiong, S., You, J. & Fan, Q. (2018). Depuration and starvation improves flesh quality of grass carp (*Ctenopharyngodon idella*). *Aquacult. Res*. 49(9), 3196–3206. DOI: 10.1111/are.13784.

22. Marković, Z., Stanković, M., Rašković, B., Dulić, Z., Živić, I. & Poleksić, V. (2016). Comparative analysis of using cereal grains and compound feed in semi-intensive common carp pond production. *Aquacult. Int.* 24, 1699–1723. DOI: 10.1007/s10499-016-0076-z.
23. Másílko, J., Zajíc, T. & Hlaváč, D. (2015). The culture system affects organoleptic properties and lipid composition of common carp (*Cyprinus carpio* L.) meat. *J. Texture Stud.* 46(5), 345–352. DOI: 10.1111/jtxs.12134.
24. Mørkøre, T., Ruohonen, K. & Kiessling, A. (2009). Variation in texture of farmed atlantic salmon (*Salmo salar* L). Relevance of muscle fiber cross-sectional area. *J. Texture Stud.* 40(1), 1–15. DOI: 10.1111/j.1745-4603.2008.00166.x.
25. Panicz, R., Całka, B., Cubillo, A., Ferreira, J.G., Guilder, J., Kay, S., Kennerley, A., Lopes, A., e Silva, J.L., Taylor, N., Eljasik, P., Sadowski, J., Hofsoe-Oppermann, P. & Keszka, S. (2022). Impact of climate driven temperature increase on inland aquaculture: application to land-based production of common carp (*Cyprinus carpio* L.). *Transbound. Emerg. Dis*. 69(5), e2341–e2350. DOI: 10.1111/tbed.14577.
26. PN-ISO 11036:1999. (1999). Analiza sensoryczna – Metodologia – Profilowanie tekstury. Polish Committee for Standardization. Warszawa.
27. Pounds, A., Kaminski, A.M., Budhathoki, M., Gudbrandsen, O., Kok, B., Horn, S., Malcorps, W., Al Mamun, A., McGoohan, A., Newton, R., Ozretich, R. & Little, D.C. (2022). More than fish—framing aquatic animals within sustainable food systems. *Foods* 11(10), 1413. DOI: 10.3390/foods11101413.
28. Rasmussen, R.S., López-Albors, O. & Alfnes, F. (2013). Exercise effects on fish quality and implications for consumer preferences. In A. Palstra & J. Planas (Eds.), *Swimming Physiology of Fish* (pp. 275-300). Springer, Berlin, Heidelberg.
29. Rincón, L., Castro, P. L., Álvarez, B., Hernández, M. D., Álvarez, A., Claret, A., Guerrero, L. & Ginés, R. (2016). Differences in proximal and fatty acid profiles, sensory characteristics, texture, colour and muscle cellularity between wild and farmed blackspot seabream (*Pagellus bogaraveo*). *Aquaculture* 451, 195–204. DOI: 10.1016/j.aquaculture.2015.09.016.
30. Skałecki, P., Florek, M., Pyć, A., Kaliniak, A. & Staszowska, A. (2016). Comparison of physicochemical properties, fatty acid composition and mineral contents in common carp (*Cyprinus carpio* L.) fillet and the native traditional product carp ham. *PJFNS* 66(4), 311–320. DOI: 10.1515/pjfns-2015-0058.
31. Sobczak, M., Panicz, R., Eljasik, P., Sadowski, J., Tórz, A., Żochowska-Kujawska, J., Barbosa, V., Domingues, V., Marques, A. & Dias J. (2020). Quality improvement of common carp (*Cyprinus carpio* L.) meat fortified with n-3 PUFA. Food Chem. Toxicol. 139, 111261. DOI: 10.1016/j.fct.2020.111261.
32. Viana, F.M., Monteiro, M.L.G., Ferrari, R.G., Mutz, Y.S., Martins, I.B.A., Salim, A.P.A.A., De Alcantara, M., Deliza, R., Mano, S.B. & Conte-Junior, C.A. (2022). Multivariate nature of fish freshness evaluation by consumers. *Foods* 11, 2144. DOI: 10.3390/foods11142144.
33. Weatherley, A.H., Gill, H.S. & Lobo, A.F. (1988). Recruitment and maximal diameter of axial muscle-fibers in teleosts and their relationship to somatic growth and ultimate size. Journal Fish Biol. 33**,** 851–859. DOI: 10.1111/j.1095-8649.1988.tb05532.x.
34. Zhang, W., Belton, B., Edwards, P., Henriksson, P.J., Little, D.C., Newton, R. & Troell, M. (2022). Aquaculture will continue to depend more on land than sea. *Nature* 603(7900): E2–E4. DOI: 10.1038/s41586-021-04331-3.
35. Zhou, Y., Zhang, Y., Liang, J., Hong, H., Luo, Y., Li, B. & Tan, Y. (2023). From formation to solutions: Off-flavors and innovative removal strategies for farmed freshwater fish. *Trends Food Sci. Technol.* 104318. DOI: 10.1016/j.tifs.2023.104318.