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Evaluating the fillet quality and sensory characteristics of Atlantic salmon (*Salmo salar*) fed black soldier fly larvae meal for whole production cycle in sea cages

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ABSTRACT

There is scarce research on the use of black soldier fly larvae (BSFL) meal in the diets of Atlantic salmon (*Salmo salar*) reared in a real farm. Thus, the current study aimed to evaluate the effect of feeding BSFL meal to salmon in terms of fillet quality and sensory analysis at farm level conditions. Fish were fed a total of three diets (pellet size; 4.5 mm and 9 mm); a control diet (Control: 0% BSFL meal) formulated using a standard commercial recipe, containing FM (10%) and plant-based proteins. Two experimental diets were formulated using partially defatted BSFL meal (53% crude protein), in which plant-based proteins at 37% inclusion level from the control diet (4.5 mm pellets) were replaced by BSFL meal at 5% (BSFL 5%) and 10% (BSFL 10%). While for the 9.0 mm pellets, plant-based proteins at 35% were replaced by the BSFL meal at 5% and 10% inclusion level. All the three diets were formulated to be iso-nitrogenous and iso-lipidic diets. Diets were assigned to the sea-cages in triplicate (12 $\times$12 m; 1900 m^3); housing ~6000 fish per cage from 173 $\pm$ 2.7 g to harvest size 3.45 $\pm$ 74 kg for a period of 13 months. Feeding salmon with BSFL meal had no negative impact on the general fillet physical, chemical, and nutritional parameters. The fillet sensory evaluation showed that the control samples were associated with the typical attributes such as fresh salmon taste, while BSLF 10% to rancid taste but these attributes were not significantly different among the dietary groups. Overall, the current study showed that diet containing BSFL meal did not affect the general fillet parameters compared to salmon fed a commercial diet and thus validate the inclusion of BSFL meal up to 10% reared for a whole production cycle in sea cages.

1. Introduction

Fish and seafood are widely recognized for their key role in food security and nutrition, providing essential proteins, omega-3 fatty acids and micronutrients (FAO, 2020). Moreover, the global fish consumption per capita has roughly doubled over the last 50 years (Edwards et al., 2019; Naylor et al., 2021) and is expected to increase as the world population is reaching around 10 billion people by 2050 (United Nations, 2019). The aquaculture sector is one of the fastest growing food production sectors, playing a significant role in fulfilling this global demand for fish (FAO, 2020). Countries like Norway, Chile, and China are among the dominant players in global aquaculture in Europe, America, and Asia, respectively (FAO, 2020). In Norway, a significant area of aquaculture revolves around the culture and production of Atlantic salmon (Asche et al., 2013). Salmon has a high market value, and its elite image is due to its characteristic red-to-pink fillet color, with

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a good amount of proteins, long chain poly-unsaturated fatty acids, minerals, and vitamins (Lu, 2022). Also, consumption of salmon is associated with a reduced risk of cardiovascular diseases and improves neurodevelopment in infants (EFSA, 2015). Hence, the production of a high-quality fillet is a crucial aspect of salmon aquaculture, as it can directly affect the nutritional quality, consumer preference and market value of salmon (Anderson, 2001; Vanhonacker et al., 2013).

The quality of salmon fillets is affected by the feed composition, and salmon aquaculture strongly relies on the utilization of multiple ingredients to produce a good quality feed (Boyd et al., 2020). Traditionally, fish meal (FM) and fish oil are the major ingredients in a typical Norwegian salmon feed (Aas et al., 2022). However, rapid growth in aquaculture and limited availability and sustainability issues of these ingredients led to changes in the salmon feed formulation and manufacturing (Aas et al., 2022; Lutfi et al., 2023). Efforts were made to reduce and/or replace FM through the inclusion of alternative sources of ingredients from terrestrial plants, animal by-products, microalgae, macroalgae or insects into salmon feed (Barroso et al., 2014; Boyd and McNevin, 2015; Gatlin III et al., 2007; Wan et al., 2019). Studies have reported that inclusion of alternative ingredients such as krill meal, microalgae, and their levels in feed can influence the physical, chemical, nutritional and sensory properties of fillet (Kousoulaki et al., 2016; Larsson et al., 2014; Lutfi et al., 2023; Mørkøre et al., 2020; Turchini et al., 2009). Among the suggested alternative ingredients, the black soldier fly larvae (BSFL) (*Hermetia illucens*) a dipteran insect species, has drawn global attention as an alternative for replacing the traditional protein sources (e.g., FM or soy protein) in aquaculture feeds due to their favorable amount of protein (~ 40% of dry weight) and suitable amino acid profile (Smetana et al., 2019; Weththasinghe et al., 2021). The insect has a faster growth rate, less rearing time (Gasco et al., 2020) and has the capability to convert food waste into protein and fat for animal feed, making it a good fit into the circular economy strategy (Kee et al., 2023).

Studies performed on fish species showed that the fillet proximate composition, fatty acid (FA) profile, textural properties and sensory analysis are influenced by dietary inclusion of BSFL meal (St-Hilaire et al., 2007; Sealey et al., 2011; Lock et al., 2016). For instance, the levels of essential amino acid levels in the whole-body composition were found to be higher in juvenile barramundi when fed a BSFL-based diet after 8 weeks of feeding (Katya et al., 2017). Regarding the fatty acid profile, it was observed that feeding high levels of BSFL meal to rainbow trout (40% inclusion level; Renna et al., 2017; Mancini et al., 2018; Secci et al., 2019) or Jian carp (14% inclusion level; Zhou et al., 2018) decreased polyunsaturated fatty acid (PUFA) and increased the saturated FA (SFA) content (Fischer et al., 2021). Also, Belghit et al. (2019) reported that the amount of SFA doubled at dietary inclusion of BSFL at 85% in salmon feed (Belghit et al., 2019). Modulation in fatty acid and lipid content due to dietary inclusion of insect meal are expected to affect the flesh texture such as juiciness and tenderness (Johansson et al., 2000) and in a study conducted by Borgogno et al. (2017) reported decreased fibrousness and onset of metallic flavor in rainbow trout (25% and 50% inclusion level). However, a 16-week study on post-smolt salmon reported no significant differences in fillet sensory characteristics when dietary FM was completely replaced by BSFL meal (Belghit et al., 2019; Lock et al., 2016). In rainbow trout, partial replacement of dietary FM with 50% of BSFL meal did not impair the fillet's physical traits, nutritional value, and yield when fed for 14 weeks (Bruni et al., 2020b). However, a decrease in the omega 3 fatty acid was observed when FM was partially replaced with dietary BSFL meal (30% FM replacement) in rainbow trout fed for 7 weeks (Melenchón et al., 2021). Renna et al. (2017) also observed an increase in fat content of rainbow trout fillet when 50% FM in the diet was substituted by BSFL meal when fed for 12 weeks. All these studies report the effects of dietary inclusion of BSFL meal in the fish fillet and these differences could be probably due to different processing and rearing substrate used for the insects. Also, most of these trials examining the fillet parameters were conducted under controlled and stable laboratory conditions for a limited time. In contrast, commercial-scale fish farming presents different challenges such as delousing and handling, along with various uncontrollable factors like water temperature, turbidity, salinity, and oxygen levels. Nevertheless, the current study along with Eide et al. (2024) were the initial study to examine the effects of dietary BSFL meal on growth and health of Atlantic salmon under real farm conditions.

To date, no study has explored how BSFL-based diets affect salmon fillets when included in a commercial diet for a long term, exposed to farming challenges. Therefore, the aim of the study is to assess the effect on salmon fillet quality and sensory characteristics when BSFL meal is included at different levels in a commercial-type diet fed to Atlantic salmon through the whole sea water production phase.

2. Materials and methods

2.1. Black soldier fly larvae meal

BSFL meal was produced by Protix Biosystems BV (Dongen, The Netherlands). The BSFL meal contains 53% crude protein and 13% crude lipid. The larvae were fed on plant-based waste streams. The chemical composition and total amino acid composition of BSFL meal are presented in Table 1.

2.2. Experimental diets and chemical composition

A detailed description of the experimental diets has been published elsewhere (Radhakrishnan et al., in press). In brief, the experimental diets were produced by Skretting Norway (Averøy, Norway). A control diet (Control) was formulated using a standard commercial recipe (Table 2). BSFL meal was added to the two experimental diets at 5% (BSFL 5%) and 10% (BSFL 10%) of the diet, replacing the vegetable protein (guar meal, horse beans, sunflower meal and soy protein

Table 1
Chemical, amino acid and mineral composition of black soldier fly larvae (BSFL) meal.

	BSFL meal
Chemical composition (%)	
Crude Protein	53.0
Crude Lipid	13.4
Amino acid composition (mg/g)	
His	13.5
Ser	20.9
Arg	24.1
Gly	24.2
Asp	51.0
Glu	58.0
Thr	20.8
Ala	31.0
Pro	27.8
Lys	35.0
Tyr	28.0
Met	9.5
Val	29.7
Ile	23.4
Leu	36.0
Phe	22.1
Mineral composition (mg/g)	
P	12.0
Ca	8.2
Mg	4.1
K	10
Se	0.00021
Mn	0.3
Zn	0.19
Fe	0.3
Cu	0.014
As	0.00011

BSFL= black soldier fly larvae

Table 2
Formulation and proximate composition (% of dry matter) of experimental diets (4.5 and 9.0 mm) fed to Atlantic salmon during 13 months in open sea cages (Previously published in Radhakrishnan et al., in press).

Ingredients	4.5 mm			9.0 mm		
	Control	BSFL 5%	BSFL 10%	Control	BSFL 5%	BSFL 10%
Fishmeal[a]	10.0	10.0	10.0	10.0	10.0	10.0
Guar Meal 58% CP roasted[2]	10.0	8.10	5.00	12.0	8.4	4.8
Horse beans dehulled[3]	8.58	7.00	6.75	5.5	4.8	4.8
Soy protein concentrate[4]	19.0	17.7	16.1	7.0	6.0	4.0
Sunflower meal[5]	-	-	-	7.0	7.0	7.0
BSF larvae meal[6]	-	5.00	10.0	-	5.0	10.0
Fish oil crude high[7]	4.52	4.45	4.37	5.10	5.04	4.96
Fish oil crude low[8]	4.22	4.44	4.60	4.25	4.38	4.50
Rapeseed oil[9]	14.2	13.7	13.2	22.80	22.53	22.17
Camelina oil[10]	-	-	-	2.55	2,34	2,12
Wheat[11]	4.00	4.00	4.00	7.7	7.7	7.7
Wheat gluten vital pellets[12]	20.0	20.0	20.0	11.76	12.42	13.67
Micro-nutrients[13]	2.98	3.04	3.06	2.15	2.16	2.20
Vitamin-mineral mix[13]	0.81	0.80	0.80	0.86	0.87	0.87
Water	1.68	1.77	2.15	1.32	1.33	1.28
Proximate composition						
Dry Matter %	92.8	92.3	93.5	94.2	93. 9	93.4
Moisture %	7.2	7.8	6.5	5.76	6.11	6.63
Crude Protein %	49.0	48.0	49.0	41.0	42.0	41.0
Crude lipid%	24.0	27.0	25.0	31.0	33.0	33.0
Ash %	4.5	4.5	4.7	4.5	4.8	4.7
TBARS (nmol/g ww)	8.1	10.0	12.0	12.0	13.0	15.0
Gross energy (MJ/kg)	24.6	26.1	25.2	26.2	26.4	26.6

[a] North Atlantic, min. 64% protein; [2]Roasted, min. 53% protein; [3]Dehulled, min. 25% protein; [4]Non-GM, min.58% protein; [5]Min. 34% protein; [6]Protix; [7]North Atlantic; [8]South American; [9]Degummed; [10]Degummed; [11]Min. 10% protein; [12]Vital, min. 80% protein; [13]Skretting; [13]Skretting; BSF: black soldier fly; TBARS: thiobarbituric acid reactive substances. July 2021to January 2022, 4.5 mm pellet; February 2022 to August 2022, 9.0 mm pellet

concentrate). The main lipid sources in all diets were fish oil and vegetable oils (rapeseed oil and camelina oil). The three diets contained the same level of fish meal (10%) and were formulated to be iso-nitrogenous, iso-lipidic and iso-energetic diets (Table 2). The diets were extruded, and 4.5- and 9.0-mm sinking pellets were used in the trials. The diets were analyzed for dry matter (DM), proteins, lipids, ash, gross energy (GE), amino acids (AA) (not including cysteine and tryptophan), fatty acid (FA) composition, minerals and thiobarbituric acid-reactive substances (TBARS).

The chemical composition of the diets was analyzed according to AOAC (2010) methods. Samples were freeze dried for 48 h (FreeZone 18 Liter Console, Labconco, USA) to obtain the dry matter. The dried feed samples were ground into a fine powder for the analysis of nitrogen (N), fat and ash content. Nitrogen content was analyzed using a CHNS elemental analyzer (Vario Macro Cube, Elementar Analysensysteme GmbH, Langenselbold, Germany) and quantified (Dumas, 1832). The instrument was calibrated with Ethylenediamine tetraacetic acid (Leco Corporation, Saint Joseph, MI, USA). Sulfanilamide (Alfa Aesar GmbH & Co, Karlsruhe, Germany) and a standard meat reference material (SMRD 2000, LGC Standards, Teddington, UK) were used as control sample. Crude protein was calculated as N% × 6.25. Crude lipid was measured gravimetrically after acid hydrolysis. Thiobarbituric acid-reactive substances (TBARS) were determined according to Schmedes and Hølmer (1989). The absorbance of TBARS were measured at 532 nm and quantified using an external standard. Gross energy was measured by adiabatic bomb calorimetry using manufactures protocol (Parr Instrument Co., Moline, IL, USA). The feed formulation and analyzed nutrient composition of the feeds are provided in Table 2. The amino acid analysis of the diets was carried out by an ultra-performance liquid chromatography (UPLC, Waters Acquity UPLC system, Milford, MA, USA). The quantitative determination was based on an accredited method by the Nordic Committee of Food Analysis (NMKL) and described in detail elsewhere (Belghit et al., 2018). The results were integrated by Empower 3 (Waters, Milford, MA, USA). Amino acids were quantified using standards from Thermo Fisher Scientific (product number; 20088 Rockford, IL 61105, USA). The fatty acid composition of diets was determined according to the method described by Lie and Lambertsen (1991), using gas liquid chromatography (Scion 436-GC, Scion Instruments, UK). The FA were identified by their retention times using a standard mixture of methyl esters (Nu-Chek-Prep, Elysian, MN, USA). The quantification of the FA was carried out by using 19:0 as internal standard and the FA composition expressed in absolute units (mg/g). Chromeleon® version 7.2 (Thermo Scientific, Waltham, MA, USA) software was used for the integration of chromatographic peak areas. The mineral concentration in the diet was determined by inductively coupled plasma mass spectrometry (ICP-MS) (iCapQ ICPMS, ThermoFisher Scientific, Waltham, MA, USA) equipped with an autosampler (FAST SC-4Q DX, Elemental Scientific, Omaha, NE, USA.) after wet digestion in a microwave oven, as described by Liland et al. (2017). Data were collected and processed using the Qtegra ICP-MS software (Thermo Scientific, version 2.10, 2018).

The proximate compositions of the experimental diets were similar in DM (93–94%), and ash (4.5–4.8%) (Table 2). The crude protein was similar and ranged between 48–49 and 41–42% for 4.5 mm and 9.0 mm diet, respectively. Diets containing BSFL meal had higher crude lipid than the control diet. Likewise, TBARS were also slightly higher in BSFL meal diets ranging from 8–12 (4.5 mm) and 12–15 nmol/g (9.0 mm) compared to the control diet. The GE values were slightly different for 4.5 mm diets (24–26 MJ/kg) but were similar for 9.0 mm diets (26.2–26.6 MJ/kg). Furthermore, the FA composition varied across the diets (Supplementary Table 1). These variations were more marked in lauric acid (C12), which is a typical fatty acid for the species of BSFL, and below the quantification level in control diet. Similarly, the sum of saturated fatty acids and mono-unsaturated fatty acids were higher in the insect fed diet than the control diet. The concentration of marine omega 3, like eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) was similar between the three diets. The PUFA content was also stable across the control and diets containing insect meal (Supplementary Table 1). The three experimental diets had close to identical concentrations of amino acids and minerals (Supplementary Table 1).

2.3. Experimental trial and farming conditions

A detailed description of the experimental trial has been published elsewhere (Radhakrishnan et al., in press). In short, the feeding trial was conducted at Austevoll research station, Institute of Marine Research, Norway, from July 2021 to August 2022 (13 months). Approximatively 6000 fish were distributed into each sea-cage using sensors, which detect and record the fish before releasing them into each cage. The fish were randomly distributed into nine open sea-cages (12 ×12 m2;1922 m3). Diets were assigned to the sea-cages in triplicates using a randomized block design, containing three blocks (B1, B2, and B3) to account for cage position effects. The fish were acclimatized to the control diet one week prior to the start of the experiment. The feed was dispersed using automatic surface feeders with meals given every 3 min during seven hours a day (20 doses/h). The feeding volume were recorded and registered daily using the Mercatus Farmer software (Scale AQ, Norway) to estimate the biomass and feed conversion ratio. The pellet size (4.5- and 9.0-mm pellet) and size of meals were adjusted

according to the fish size, biomass and feeding behavior by visual observation from the surface. Lumpfish (*Cyclopterus lumpus*) and Ballan wrasse (*Labrus bergylta*) were added to each cage to keep lice levels low, according to standard routines at the station (Ratio of cleaner fish to salmon was 12% with the same ratio in all cages).

Temperature, dissolved oxygen and salinity in the Austevoll research station were monitored throughout the year using Mercatus software (Scale AQ, Norway). The monthly average for temperature (°C), salinity (‰) and oxygen (% of saturation) (10 m depth) for an entire year from July 2021- August 2022, ranged between 6–15 °C, 17–30‰, and 94–108 (% of saturation), respectively.

2.4. Sampling

For the collection of fish from the sea cage with a minimum of stress, a large net hung from one side of the cage was used for each sampling. The net caught the jumping fish in a smaller and separate section of the cage. Fish from this smaller and shallower section were taken out of the sea cage using hand nets and transferred to large tubs. Fish were then anesthetized with Finquel vet. (Tricaine Mesylate) in a separate and smaller water tub.

From the final sampling, six fish per cage were overdosed with anesthesia (60 mg/L) and killed by cephalic concussion before removing and weighing the liver and viscera for calculations of organ somatic indices. A standardized fillet sample was taken from the same fish, according to the Norwegian Quality Cut (NQC) as described by Johnsen et al. (2011) and stored at − 30 °C to examine their chemical composition. Six additional salmon from each sea cage were killed to remove the right and left fillets. These fillets were vacuum packaged in plastic bags, frozen, packed with dry ice and shipped to Italy (Department of Agricultural, Forest and Food Sciences, University of Turin) for calculating their physical quality parameters. Additionally, seven fish from each cage (21 fish total per diet) were killed using percussive stun followed by removing scales, head and tail. The fish was eviscerated, washed, packaged in plastic bags, frozen, and stored. These were later packed with dry ice and shipped to Portugal (Sense Test, a consumer testing and sensory evaluation company) for sensory analysis.

2.5. Analysis of physical quality parameters

2.5.1. Fillet water losses

To calculate drip loss, the left fillets (six fish/cage) were weighed, packed in a plastic bag, and refrigerated at 4 °C. After 24 h, the excess moisture from the fillets was gently removed with a paper, and the fillets were weighed. The same fillets were then individually vacuum-packaged and stored at − 20 °C until further analysis. These fillets were later thawed at 4 °C, dried with paper, and weighed to calculate the thawing loss. The same fillets were again vacuum packaged and cooked in a fish kettle for 40 min at 52 °C. After cooking, the bags were removed from the fish kettle and cooled in running fresh water for 15–20 min to stop the cooking process. The fillets were then removed from the bags, dried with paper, and weighed to calculate the cooking loss. All formulae for water losses are as described elsewhere (Caimi et al., 2021).

2.5.2. Shear force of cooked fillet

The texture of the cooked fillets (shear force) was measured using an Instron 5543 Universal Testing Machine (Instron Corporation, Canton, Massachusetts, USA), equipped with a shear blade (crosshead speed of 30 mm/min) (Caimi et al., 2021).

2.5.3. Colorimetric analyses of fillets

The right fillet was used to measure the color on the inside portion of the cranial, medial, and caudal region of each fillet using a Chroma Meter CR-400 (Konica Minolta Sensing Inc., Osaka, Japan). The color was expressed in terms of lightness (L), redness (a) and yellowness (b).

2.6. Analysis of chemical composition

The chemical composition of the fillets (obtained by NQC) for dry matter, protein, ash, fatty acids, minerals are as described in Section 2.1. The crude lipid was measured gravimetrically after ethyl acetate extraction for fillet samples. Vitamin E (tocopherol and tocotrienol) in the fillet were analyzed using high performance liquid chromatography (HPLC) coupled with a fluorescence detector (Ultimate 3000 series, Dionex, Sunnyvale, CA, USA) according to Konings et al. (1996) as explained by Hamre et al. (2010). The tocopherol and tocotrienol species were quantified by using external standards.

2.7. Salmon sensory analysis

For the sensory evaluation of the salmon, a total of 80 untrained panelists (naïve consumers) residents of the Porto metropolitan area, North of Portugal, were recruited from the sensory evaluation company Sense Test's consumer database (Vila Nova de Gaia, Portugal). All participants were regular consumers of fish at least two times per week and were selected based on their willingness to try products containing edible insects (Ribeiro et al., 2022). The company ensures the protection and confidentiality of data through the authorization 2063/2009 of the National Data Protection Commission and following the EU General Data Protection Regulation (EU 2016/679), as well as a longstanding internal code of conduct, assuring informed consent. Sensory evaluation was carried out in individual tasting booths in a special room equipped in accordance with ISO 8589:2007 - Sensory analysis - General guidance for the design of test rooms. The panelists evaluated overall liking using a 9-point hedonic scale, ranging from 1-"dislike extremely" to 9-"like extremely" (Peryam and Pilgrim, 1957). For each sample, the overall liking evaluation was immediately followed by the evaluation of the sensory profile, through the Rate-All-That-Apply (RATA) methodology, as suggested by Ares and Jaeger (2013a) and King et al. (2013) to reduce bias.

2.7.1. Sample preparation and presentation

Prior to the evaluation, salmon were thawed, cleaned and sliced (up to nine slices), with approximately 2 cm of thickness were cut from each fish and cooked for 12 min at 100 ºC in an industrial convection oven (Rational International AG). Samples were presented on white porcelain dishes coded with a three-digit random number. To compensate for eventual carry-over effects, each panelist received a set of four samples (CTRL in duplicate to evaluate internal variability), following a monadic sequential presentation, with their order previously balanced, in accordance with MacFie et al. (1989). Participants were instructed to chew a small bit of a plain cracker and to rinse their mouth with water, before each evaluation.

2.7.2. RATA (Rate-All-That-Apply)

The list of terms included in the RATA ballot was generated by the research team. The list of attributes was compiled based on a comprehensive review of the literature combining previously published studies and considering the consumers feedback and results from previous studies at the lab. A final ballot of 24 sensory attributes was obtained, with attributes organized by sensory dimension (appearance, odor, texture and taste) to reduce the cognitive effort required by the participants (Ares et al., 2013) (Supplementary table 2). While fixing the order of the sensory dimensions, individual attributes within each sensory dimension were presented in a randomized order of presentation, different for each participant and each product (Ares et al., 2014). Panelists were asked to check the terms they considered applicable for describing samples and then to rate the intensity of each selected attribute, using a 5-point structured scale (from 1- "slightly applicable" to 5-"very applicable") (Meyners et al., 2016).

2.8. Calculations

$$\text{Drip loss}(DL,\%) = [(\text{Raw fillet weight}(g) - \text{Raw fillet weight after24h}(g))/\text{Raw fillet weight}(g)] \times 100$$

$$\text{Thawing loss}(TL,\%) = [(\text{Raw fillet weight}(g) - \text{Thawed fillet weight}(g))/\text{Raw fillet weight}(g)] \times 100$$

$$\text{Cooking loss}(CL,\%) = [(\text{Raw fillet weight}(g) - \text{Cooked fillet weight}(g))/\text{Raw fillet weight}(g)] \times 100$$

$$\text{Chroma}(C) = \sqrt{(a^2 + b^2)}$$

$$\text{Change in color}(\Delta E) = \sqrt{[(L* - L)^2 + (a* - a)^2 + (b* - b)^2]};$$ L* a* , and b * represent the control group, and L, a, and b the BSFL fed group.

$$\text{Polyunsaturated to saturated fatty acid ratio PUFA/SFA} = \Sigma PUFA/\Sigma SFA$$

$$\text{Atherogenicity index}(AI) = [C12:0 + (C14:0 \times 4) + C16:0]/\Sigma UFA;$$ UFA is unsaturated fatty acid

$$\text{Thrombogenicity index}(TI) = [C14:0 + C16:0 + C18:0]\Big/[(\sum \text{MUFA} \times 0.5) + (\sum \text{PUFA n}-6 \times 0.5) + (\sum \text{PUFA n}-3 \times 3) + (\sum \text{n}-3 \Big/ \sum \text{n}-6)]$$

$$\text{Health}-\text{promoting index}(HPI) = \Sigma UFA/[C12:0 + C14:0 + C16:0]$$

$$\text{Flesh lipid quality}(FLQ) = 100 \times (22:6n-3 + 20:5n-3)\Big/\sum FA$$

$$\text{Omega}-3\Big/\text{omega}-6\text{ratio} = \sum \text{PUFA n}-3\Big/\sum \text{PUFA n}-6$$

2.9. Statistical analysis

All the statistical analyses were done using Statistica 13.4 (Statsoft Inc.) and GraphPad Prism version 9.0.0 (GraphPad Software, La Jolla California USA, www.graphpad. com). Data were tested for homogeneity of variance and normality using a Kolomogorov–Smirnov test and Shapiro–wilk test respectively. Parametric and non-parametric tests were performed for normal and non-normal distributed data, respectively. A randomized block design (RBD) with three blocks (B1, B2 and B3) was used to determine the effect of the positions of cages. Data from fillet quality were subjected to nested two-way ANOVA with diet and block as the two main variables and cages as a random effect factor.

To evaluate the results of the overall liking a two-way mixed effects ANOVA, with consumers as a random factor and diet as fixed factor, was applied. From the RATA evaluation, a data set was generated with the RATA applicability (0 = "not applicable"; 1 = "slightly applicable" to 5 = "very applicable") that was analyzed following an approach similar to the one described by Baião et al. (2022). The effect of diet on the RATA scores for the sensory descriptors of the product was tested by a one-way ANOVA to identify which attributes were discriminating among samples. Correspondence Analysis (CA) was performed, considering Hellinger's distances, on the sum of scores given by all consumers to each term for describing each sample (RATA scoring). Such analysis provides a sensory map of the samples, allowing for the perception of the similarities and differences between samples and their sensory characteristics (Baião et al., 2022). When significant effects, at a 95% confidence level, were identified a Tukey's multiple comparisons test or a Kruskal–Wallis non-parametric analysis, using the median test and multiple pairwise comparisons by ranks were applied. For all statistical tests, P-values < 0.05 were considered significant. The results are expressed as mean ± standard error.

3. Results

3.1. Growth performances

The growth performances and mortality of salmon fed BSFL meal have been described elsewhere (Radhakrishnan et al., in press). In summary, the results showed that after 13 months, the fish had grown ~20 times fold (3397 ± 74 g) of the initial body weight (173 ± 250 g). Dietary BSF inclusion did not affect specific growth rate (1.4 ± 0.03%), weight gain (3243 ± 137%) or survival rate (64 ± 3.5%) (Radhakrishnan et al., in press).

3.2. Physical quality

The physical fillet quality parameters (Table 3) such as water losses, texture, and color of the fillets were not significantly affected by the diets ($P > 0.05$). Among the water holding capacity of the fillet, cooking loss (10–11%) was higher than drip loss (1.2–1.8%). The textural property measured in this study was the shear force (N), which ranged between 24–26% among the groups. Similarly, no significant difference was observed between the colorimetric measurements from different positions (dorsal, median, and caudal) between the control and BSFL-

Table 3
Water holding capacity parameters and colorimetry analysis of the fillets of Atlantic salmon fed experimental diets after 13 months of being fed in open sea cages.

Physical fillet parameters	Control	BSFL 5%	BSFL 10%	P-value
Liquid losses				
Drip loss	1.8 ± 0.27	1.2 ± 0.45	1.6 ± 0.20	ns
Thawing loss	5.9 ± 0.35	5.3 ± 0.59	5.4 ± 0.39	ns
Cooking loss	11.2 ± 0.52	10.4 ± 0.53	10.8 ± 0.50	ns
Texture properties				
Shear force (N)	25.9 ± 0.69	24.3 ± 0.97	25.3 ± 1.23	ns
Colorimetry				
Cranial				
L	50.7 ± 0.85	51.3 ± 0.41	50.8 ± 0.60	ns
a	9.1 ± 0.47	8.6 ± 0.55	9.2 ± 0.45	ns
b	25.8 ± 0.89	24.8 ± 0.69	24.8 ± 0.69	ns
C	27.4 ± 0.98	26.3 ± 0.81	26.5 ± 0.71	ns
Median				
L	49.4 ± 0.94	49.2 ± 0.64	48.7 ± 0.99	ns
a	9.3 ± 0.42	9.0 ± 0.51	9.5 ± 0.48	ns
b	25.8 ± 0.74	24.7 ± 0.75	25.3 ± 0.62	ns
C	27.4 ± 0.81	26.3 ± 0.87	27.1 ± 0.73	ns
Caudal				
L	48.7 ± 1.01	51.7 ± 1.12	49.7 ± 1.02	ns
a	9.6 ± 0.42	9.0 ± 0.93	9.0 ± 0.49	ns
b	25.9 ± 0.89	26.7 ± 1.41	25.5 ± 0.92	ns
C	27.7 ± 0.96	28.2 ± 1.60	27.0 ± 0.99	ns

BSFL: black soldier fly larvae meal; BSFL 5%: black soldier fly larvae meal included at 5%; BSFL 10%: black soldier fly larvae meal included at 10%. L: lightness; a: redness; b: yellowness; C: Chroma; ns: not significant. Physical fillet parameters were calculated using six fish per cage (triplicate cages per diet). Values are expressed as mean ± standard error.

based diets.

3.3. Fillet chemical and fatty acids composition

The chemical and fatty acids composition of the fillet from the experimental groups are described in Table 4. The chemical composition such as DM (35%), crude protein (21%), and crude lipid (10%) of the fillet were similar and not statistically different ($P > 0.05$) between the experimental groups. However, saturated fatty acid such as lauric acid was significantly higher ($P < 0.01$) in both BSFL-based diets (5% and 10%) compared to control diet. Conversely, the omega-3 poly-unsaturated fatty acid, such as docosapentaenoic acid (DPA) was significantly higher in control diet than BSFL 10% ($P < 0.01$) (Table 4).

3.4. Nutritional quality indices of fillet

Nutritional quality indices for salmon were calculated from the fillet fatty acid profile (Table 5). The polyunsaturated to saturated fatty acids ratio (PUFA/SFA), atherogenicity index (AI), thrombogenicity index (TI), health-promoting index (HPI) were significantly different among the dietary groups. The PUFA/SFA and HPI were significantly lower in BSFL 10% compared to control ($P < 0.01$), whereas the inverse trend was observed for AI and TI which were significantly higher in BSFL 10% group ($P < 0.01$). The differences for flesh lipid quality and n-3/n-6 ratio were non-significant between the three dietary groups ($P > 0.05$).

The results for vitamin E and mineral composition of the fillets from salmon fed experimental diets are provided in Table 6. The α-tocopherol, γ-tocopherol, and δ-tocopherol were not significantly different among the experimental groups. However, a slight yet higher β-tocopherol was observed in the fillet of BSFL 10% diet group compared to control and BSFL 5% ($P < 0.05$). The minerals, levels of calcium (Ca), copper (Cu), magnesium (Mg), manganese (Mn), sodium (Na), phosphorus (P), and selenium (Se) were not significant between the experimental dietary groups ($P > 0.05$). In contrast, the concentration of Zinc (Zn), iron (Fe) and Arsenic (As) were significantly different among the groups ($P < 0.05$), with BSFL 10% having highest level of Zn and Fe, and lowest level of As compared to control diet (Table 6).

3.5. Fillet sensory analysis

The overall liking (Table 7) and sensory profile of the fillet (Fig. 1) were not significantly different among the dietary groups. However, correspondence analysis (Fig. 2), showed that the control samples were associated with the typical attributes, 'fresh fish taste' and 'greasy' (appearance, texture and taste), while BSLF 5% sample were more associated with 'dryness', and BSLF 10% to 'rancid' (odor and taste), and 'bitter taste' and 'sour odor'.

4. Discussion

The current study helps to fill the existing knowledge gaps on the fillet quality when Atlantic salmon fed dietary BSFL under industry-relevant farm conditions. Two levels of dietary inclusion for BSFL meal were selected in the present study, considering the current availability (5%) and a potential future standard for insect protein meals in animal diets (10%) (Veldkamp et al., 2022). The results suggest that dietary inclusion of BSFL meal can replace the traditional plant-based protein sources in the diet of Atlantic salmon. Also, salmon performed similar irrespective of the dietary groups. Hence, in a broader perspective, the trial provides information of the impact of insect proteins on commercial aquafeed from a fillet nutritional and quality perspective.

The fillet quality parameters play a significant role in consumer acceptance and thus the market value. Starting with the physical traits, especially the fillet color is an important factor in visually judging fillet preferences (Nesic and Zagon, 2019). Results on fillet color are generally presented in terms of lightness (L), redness (a), and yellowness (b). The

Table 4
Proximate and fatty acid composition (mg/g of total fatty acids) of the fillets of Atlantic salmon fed experimental diets after 13 months of being fed in open sea cages.

	Control	BSFL 5%	BSFL 10%	P-value
Proximate composition (%)				
Dry matter	35.1 ± 0.49	35.8 ± 0.45	34.7 ± 0.41	ns
Crude protein	20.9 ± 0.20	20.8 ± 0.14	20.7 ± 0.12	ns
Crude lipid	11.8 ± 2.93	10.4 ± 0.78	10.4 ± 0.55	ns
Fatty acid composition (mg/g)				
ΣSFA	18.7 ± 0.80	18.7 ± 0.81	18.8 ± 0.64	ns
12:0	0.01 ± 0.00^{c}	0.48 ± 0.03^{b}	1.03 ± 0.04^{a}	< 0.01
14:0	2.8 ± 0.12	2.8 ± 0.12	2.8 ± 0.10	ns
15:0	0.2 ± 0.01	0.2 ± 0.01	0.2 ± 0.01	ns
16:0	11.6 ± 0.49	11.4 ± 0.49	11.1 ± 0.37	ns
17:0	0.2 ± 0.01	0.2 ± 0.01	0.2 ± 0.01	ns
18:0	3.2 ± 0.16	3.1 ± 0.13	2.9 ± 0.10	ns
20:0	0.38 ± 0.02	0.37 ± 0.02	0.36 ± 0.01	ns
22:0	0.20 ± 0.008	0.19 ± 0.010	0.18 ± 0.006	ns
ΣMUFA	69.7 ± 3.29	67.1 ± 2.72	63.9 ± 2.39	ns
16:1n-9	0.3 ± 0.02	0.3 ± 0.01	0.3 ± 0.01	ns
16:1n-7	2.5 ± 0.12	2.4 ± 0.11	2.3 ± 0.08	ns
18:1n-7	3.4 ± 0.15	3.3 ± 0.13	3.1 ± 0.11	ns
18:1n-9	47.4 ± 2.29	47.8 ± 1.41	46.0 ± 1.60	ns
18:1n-11	0.4 ± 0.01	0.4 ± 0.01	0.4 ± 0.01	ns
20:1n-7	0.15 ± 0.03	0.13 ± 0.01	0.13 ± 0.01	ns
20:1n-9	5.64 ± 0.270	5.46 ± 0.256	5.15 ± 0.181	ns
20:1n-11	0.45 ± 0.03	0.43 ± 0.02	0.42 ± 0.02	ns
22:1n-9	0.81 ± 0.039	0.76 ± 0.036	0.72 ± 0.027	ns
22:1n-11	4.45 ± 0.192	4.25 ± 0.202	4.16 ± 0.148	ns
24:1n-9	0.43 ± 0.018	0.42 ± 0.021	0.42 ± 0.015	ns
ΣPUFA	38.8 ± 1.63	37.5 ± 1.44	35.8 ± 1.21	ns
16:2n-4	0.23 ± 0.01^{a}	0.21 ± 0.01^{ab}	0.19 ± 0.01^{b}	< 0.05
18:2n-6 (LA)	17.8 ± 0.79	17.1 ± 0.69	16.6 ± 0.60	ns
20:2n-6	1.14 ± 0.072	1.16 ± 0.056	1.06 ± 0.041	ns
20:3n-6	0.36 ± 0.018	0.36 ± 0.013	0.36 ± 0.019	ns
20:4n-6 (ARA)	0.67 ± 0.033	0.65 ± 0.031	0.60 ± 0.019	ns
Σn-6	20.14 ± 0.91	19.5 ± 0.77	18.8 ± 0.68	ns
18:3n-3 (ALA)	5.98 ± 0.245	5.73 ± 0.294	5.44 ± 0.173	ns
18:3n-6	0.15 ± 0.02	0.15 ± 0.01	0.16 ± 0.01	ns
18:4n-3	1.03 ± 0.034	0.98 ± 0.048	0.94 ± 0.032	ns
20:4n-3	0.96 ± 0.048	0.95 ± 0.048	0.90 ± 0.033	ns
20:5n-3 (EPA)	3.32 ± 0.121	3.13 ± 0.108	2.92 ± 0.107	ns
21:5n-3	0.24 ± 0.011	0.23 ± 0.011	0.21 ± 0.008	ns
22:5n-3 (DPA)	1.18 ± 0.071^{a}	1.12 ± 0.045^{ab}	0.98 ± 0.044^{b}	< 0.05
24:5n-3	0.09 ± 0.023	0.10 ± 0.020	0.08 ± 0.020	ns
22:6n-3 (DHA)	5.65 ± 0.192	5.58 ± 0.147	5.33 ± 0.150	ns
Σn-3	18.5 ± 0.72	17.8 ± 0.67	16.8 ± 0.53	ns
ΣEPA+DHA	8.97 ± 0.315	8.71 ± 0.249	8.25 ± 0.252	ns
n-3/n-6	0.91 ± 0.01	0.92 ± 0.01	0.89 ± 0.01	ns
ΣTFA	129.4 ± 5.82	125.6 ± 5.06	120.6 ± 4.34	ns

BSFL: black soldier fly larvae meal; BSFL 5%: black soldier fly larvae meal included at 5%; BSFL 10%: black soldier fly larvae meal included at 10%. SFA: saturated fatty acids; MUFA: mono-unsaturated fatty acids; PUFA:

polyunsaturated fatty acids; LA: linoleic acid; ARA: arachidonic acid; ALA: alpha-linolenic acid; EPA: eicosapentaenoic acid; DPA: docosapentaenoic acid; DHA: docosahexaenoic acid; TFA: total fatty acid. ns: not significant. Fillet chemical and fatty acids composition were calculated using six fish per cage (triplicate cages per diet). Values are expressed as mean ± standard error.

Table 5
Nutritional quality indices of the fillets of Atlantic salmon fed experimental diets after 13 months of being fed in open sea cages.

Quality index	Control	BSFL 5%	BSFL 10%	P-value
PUFA/SFA	2.09 ± 0.012[a]	2.02 ± 0.017[b]	1.90 ± 0.011[c]	< 0.01
AI	0.21 ± 0.01[c]	0.22 ± 0.01[b]	0.24 ± 0.01[a]	< 0.01
TI	0.17 ± 0.01[b]	0.17 ± 0.01[b]	0.18 ± 0.01[a]	< 0.01
HPI	4.76 ± 0.036[a]	4.56 ± 0.042[b]	4.24 ± 0.026[c]	< 0.01
Flesh lipid quality	7.0 ± 0.09	7.0 ± 0.08	6.9 ± 0.06	ns
n-3/n-6 ratio	0.9 ± 0.01	0.9 ± 0.01	0.9 ± 0.01	ns

BSFL 5%: black soldier fly larvae meal included at 5%; BSFL 10%: black soldier fly larvae meal included at 10%. PUFA/SFA: Polyunsaturated to saturated fatty acids ratio; AI: atherogenicity index; TI: thrombogenicity index; HPI: health-promoting index; FLQ: flesh lipid quality; n-3/n-6: omega-3/omega-6. ns: not significant. Nutritional quality indices values were calculated using six fish per cage (triplicate cages per diet). Values are expressed as mean ± standard error.

red color is usually desired by consumers, while pale color and yellowness lower the fillet quality of salmon (Koteng, 1992). Few studies reported fillet quality of Atlantic salmon fed dietary BSFL meal (Belghit et al., 2019; Bruni *et al.*, 2020a; Lock et al., 2016). In these studies, a partial or complete replacement of fish meal with BSFL meal in the diet of salmon did not affect the color of the flesh. Similarly, the present study did not detect differences in the color of fish fed control or insect-based diets. However, the values obtained for yellowness index in the current study were different than the one reported by Bruni et al. (2020a) irrespective of the experimental group. This could be attributed to factors such as storage duration and packaging. According to Chan et al. (2021), both storage and packaging can impact the yellowness index of the fillet.

In addition to the color parameters L, a and b, the change in color (ΔE) is an easy indicator that provides an overall value of fillet color changes (Sharma, 2003). It is generally considered, that if the ΔE is at or above 2.30, the change in color is noticeable to the human eye. The range of perceiving color is, however, dependent on the observer (Mokrzycki and Tatol, 2011). For instance, the following ranges for ΔE are used $0 < \Delta E < 1$: no difference; $1 < \Delta E < 2$: only expert observers can notice the difference; $2 < \Delta E < 3.5$: non-expert observer can notice the difference; $\Delta E > 5$: clear differences between colors. Earlier studies in salmonids show a stronger effect on fillet color when using BSFL meal. For instance, the ΔE values were 2.28 and 2.96 when fish meal was replaced with either full fat BSFL meal (25%) (Bruni et al., 2020b) or defatted BSFL meal (50%) (Mancini et al., 2018), respectively. In the current study, the ΔE values between the control group and the groups with 5% and 10% defatted BSFL meal replacing plant-based protein sources were measured at 1.84 and 1.05, respectively. This suggests that the differences in fillet color among the dietary groups may only be noticeable to expert observers. It is possible that replacing plant proteins with BSFL meal has a lesser impact on fillet color compared to fish meal replacement. In addition to color, the overall consistency of the fillet is greatly affected by its ability to retain water (water holding capacity), and maintain the texture (Picard et al., 2017). Calculating the water losses is an indirect method to measure the water holding capacity (Zarantoniello et al., 2022). The results from the current study did not show any dietary effects on the measured water losses, thus being in accordance with studies in salmonids where fish meal has been replaced with BSFL meal (Borgogno et al., 2017; Caimi et al., 2021; Secci et al., 2019).

Fish is one of the main sources of dietary n-3 PUFA which are required in 250 mg per day (EPA+DHA) for a human adult healthy diet

Table 6
Vitamin E and mineral composition (mg/kg) of the fillets of Atlantic salmon fed experimental diets after 13 months of being fed in open sea cages.

Vitamin E (mg/kg)	Control	BSFL 5%	BSFL 10%	P-value
α-tocopherol	51.6 ± 1.61	49.5 ± 1.96	48.3 ± 2.10	ns
β-tocopherol	0.18 ± 0.01[b]	0.20 ± 0.01[b]	0.21 ± 0.01[a]	< 0.05
γ-tocopherol	22.9 ± 1.09	22.3 ± 0.87	20.9 ± 0.73	ns
δ-tocopherol	0.3 ± 0.02	0.3 ± 0.02	0.3 ± 0.01	ns
α-tocotrienol	0.14 ± 5.99	0.14 ± 0.00	0.15 ± 0.00	ns
β-tocotrienol	1.2 ± 0.06	1.3 ± 0.07	1.3 ± 0.04	ns
Mineral composition (mg/kg)				
P	2750 ± 39.8	2800 ± 46.7	2731 ± 36.2	ns
Ca	92.7 ± 34.52	50.5 ± 2.33	47. 6 ± 1.52	ns
Mg	294.4 ± 3.53	298.5 ± 5.29	293.8 ± 3.40	ns
Na	269.4 ± 7.04	289.2 ± 16.23	256.3 ± 7.47	ns
K	4525 ± 64.9	4607 ± 93.7	4506 ± 59.5	ns
Se	0.15 ± 0.01	0.15 ± 0.01	0.15 ± 0.01	ns
Mn	0.07 ± 0.02	0.06 ± 0.01	0.06 ± 0.01	ns
Zn	3.54 ± 0.06[b]	3.75 ± 0.12[ab]	3.85 ± 0.08[a]	< 0.05
Fe	2.29 ± 0.05[b]	2.61 ± 0.14[ab]	2.60 ± 0.11[a]	< 0.05
Cu	0.38 ± 0.01	0.36 ± 0.01	0.36 ± 0.01	ns
As	0.25 ± 0.01[a]	0.23 ± 0.01[ab]	0.21 ± 0.01[b]	< 0.01

BSFL: black soldier fly larvae meal; BSFL 5%: black soldier fly larvae meal included at 5%; BSFL 10%: black soldier fly larvae meal included at 10%. ns: not significant. Values were calculated using six fish per cage (triplicate cages per diet). Values are expressed as mean ± standard error.

(EFSA, 2015; USDGA, 2015). The n-3 PUFA content in the fish fillet is greatly influenced by the fatty acid profile of the feed. The BSFL meal is known to have a high amount of SFA, especially lauric acid (Fischer et al., 2022). The BSFL meal used in this trial was partially defatted and did only lead to minor changes in fatty acid composition of the fillets, more specifically a significant increase in lauric acid and a small, but significant decrease in DPA. The content of EPA and DHA were not significantly affected by the diets, but the inclusion of partially defatted BSFL meal up to 10% inclusion had a significant effect on the unsaturation ratio due to the higher content of total SFA in insect meal-based diets (Fischer et al., 2021). A similar trend was observed when yellow meal worm was used in the diet of rainbow trout (Iaconisi et al., 2018). One of the reasons for reduced unsaturation ratio in the current study is due to the reduction of fish oil in the diet while using BSFL meal to make the diet iso-lipidic, and iso-energetic. It was studied that reduction in fish oil in the diet can reduce the n-3 PUFA levels in fillet and can affect the overall nutritional indices (Zarantoniello et al., 2022; Fischer et al., 2022). Furthermore, other indices such as AI and TI had higher values with increased dietary inclusion of BSFL meal due to higher amounts of saturated fatty acids which could indicate probable inflammatory effects on human health (Acay et al., 2014). Similar increase in these indices were observed in rainbow trout when replaced up to 50% fish meal with partially defatted BSFL meal (Bruni et al., 2020b). This may be due to the lack of n-3 PUFA in the FA profile of BSFL meal, a characteristic that is also observed in most terrestrially sourced ingredients. However, in the current study changes in these estimated nutritional indices were marginal and within the limits for salmon irrespective of the dietary group.

Table 7
Overall liking of the salmon samples.

Consumers (n = 80)	Control	BSLF 5%	BSLF 10%	P-value
Mean (6-9 overall liking)	7.2 ± 1.2	6.8 ± 1.5	6.9 ± 1.4	ns
% Positive Responses	92%	86%	90%	ns

BSFL: black soldier fly larvae meal; BSFL 5%: black soldier fly larvae meal included at 5%; BSFL 10%: black soldier fly larvae meal included at 10%. ns: not significant. Values were calculated using seven fish per cage (triplicate cages per diet). Values are expressed as mean ± standard error.

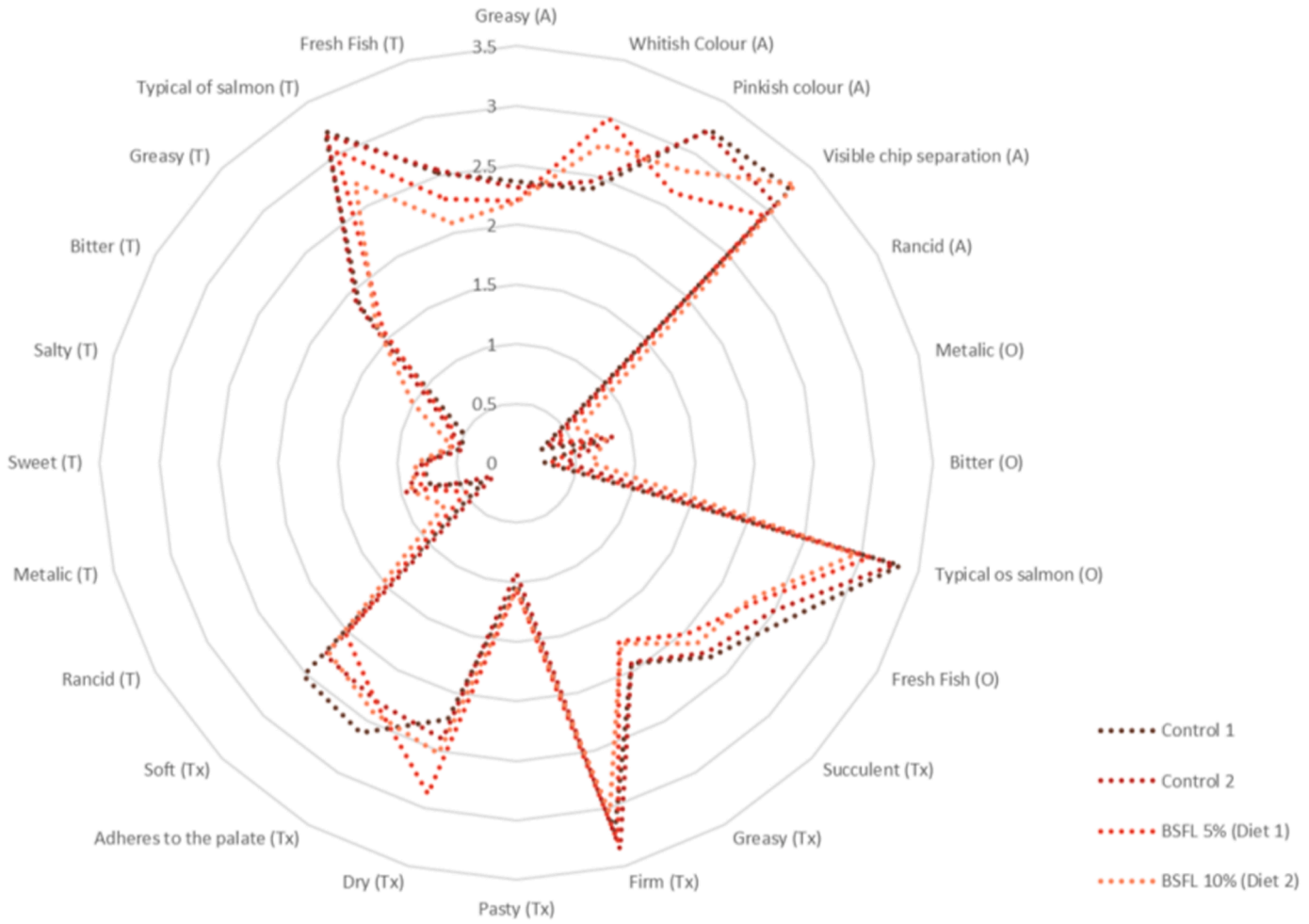

Fig. 1. : Radar plot with mean ratings of the sensory attributes of cooked fillets from Control, BSFL5% and BSFL10% fed Atlantic salmon. On scale from 1 to 5, with 1 = "slightly applicable" to 5 = "very applicable", if considered applicable. Sensory attributes ordered by sensory dimension: A - appearance, O – odor, Tx – texture and T – taste). No statistical differences were recorded between the dietary groups ($P > 0.05$, two-way mixed effects ANOVA, with consumers as a random factor and diet as fixed factor).

For example, the estimated nutritional indices for AI, TI were 0.21–1.41, and 0.14–0.87, respectively for fish species such as salmon, trout, carp, or seabass (Chen and Liu, 2020).

Furthermore, this decrease in health indices to some extent, might be partially compensated by the presence of other health benefits compounds such as vitamin-E (Turchini et al., 2009). It is reported that measuring α-tocopherol provides information on lipid oxidation and color deterioration in animal meat (Monahan et al., 1992). In the current study, the level of different components of vitamin E such as tocopherol and tocotrienol were analyzed in the fillet. No differences were observed in the current study on the level of α-tocopherol between the three dietary groups, however, an increased level of β-tocopherol was observed in BSFL at 10% inclusion. An earlier study reported a decrease in lipid oxidation when European seabass were fed diets with BSF prepupae meal compared to the control diet (fish meal by BSFL up to 19.5%;22.5% of total dietary protein) (Moutinho et al., 2021). Higher deposition of non-α-tocopherol isoforms in fish fillets adds value to the product because the potential health benefits of tocotrienols in the human diet can include potential blood cholesterol lowering effects, anti-cancer properties, cardio-protective benefits (Sambanthamurthi et al, 2000) and protection against neurodegeneration and stroke (Khanna et al, 2006). Thus, higher level of β-tocopherol could be attributed to the present of chitin in insect meals, as deacetylated form of chitin has antioxidant capacity (Georgantelis et al., 2007). Further, lipid sources that contain more SFA tend to produce fish products with increased oxidative stability, thereby enhancing shelf life (Bureau and Gibson, 2004; Bahurmiz and Ng, 2007). Thus, it could be speculated that the presence of higher levels of vitamin E levels and saturated fatty acids may have compensated for the higher level of peroxidation product (TBARS) in BSFL-based diets compared to control diet. However, it should be noted that the changes observed for nutritional indices, vitamin E were marginal and further research is needed to explain the potency, availability and health benefits of these vitamin E sources, as deposited in fish flesh.

Furthermore, an increase in zinc and iron levels were observed when salmon were fed BSFL meal up to 10% compared to control diet. Plant-based ingredients are known to contain antinutrients which can decrease mineral availability due to their high binding affinity for metal ions. Thus, the higher level of Zn and Fe observed in the current study might be the result of the reduction of plant-based ingredients in the BSFL diets. Furthermore, in the present study, a decrease in arsenic level was observed in fillet from BSFL fed group, which is in accordance with other studies conducted with partially defatted BSFL meal in freshwater Atlantic salmon (Belghit et al., 2018) probably due to the form of arsenic species in the BSFL meal that were not bioavailable in the salmon fillet.

The sensory testing conducted on the salmon fillet was unable to detect any significant difference between the control and BSFL-based diets. Similar results were obtained in studies involving trained and

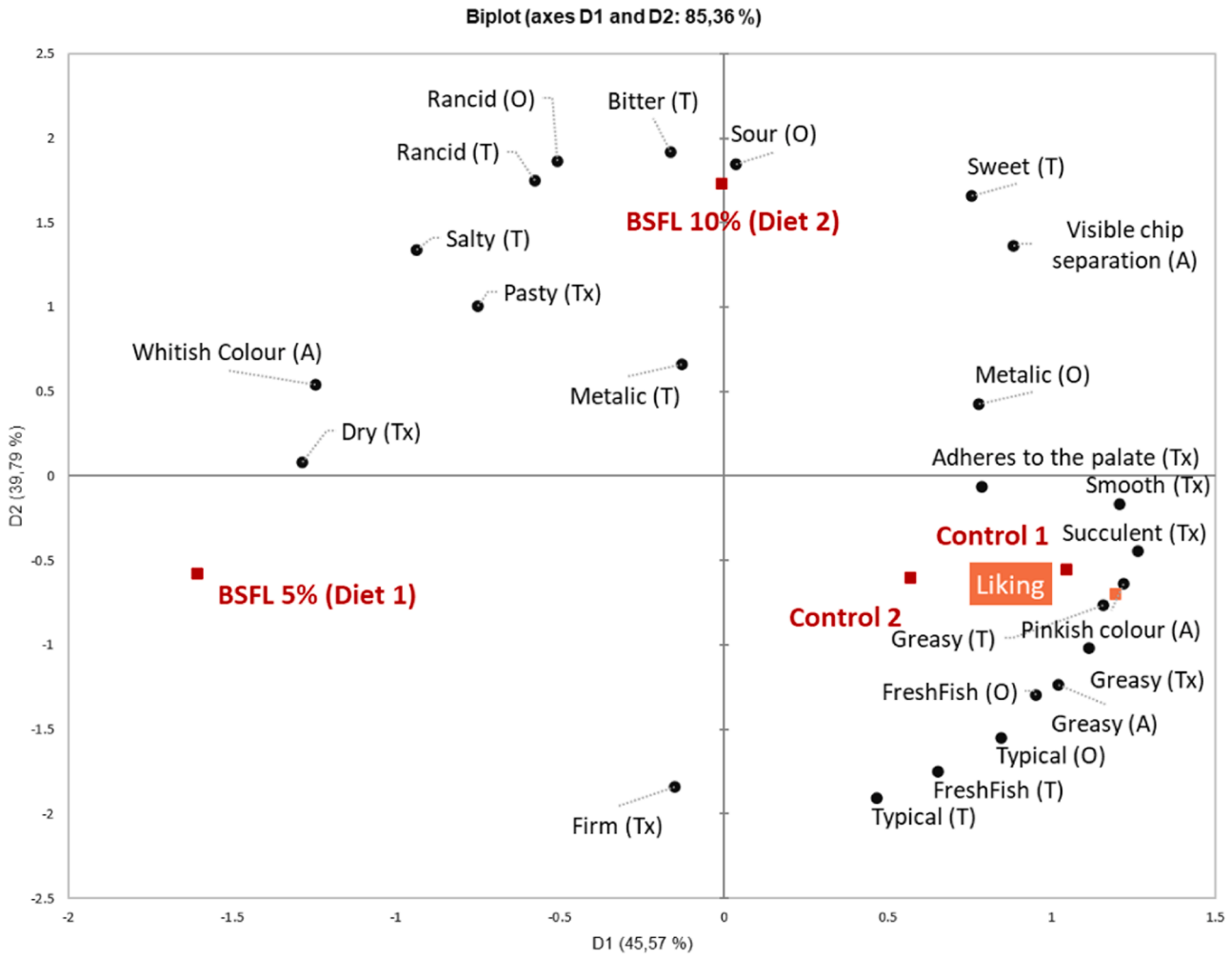

Fig. 2. : Biplots of correspondence analysis (CA) of RATA (Rate-All-That-Apply) data from the sensory profiling of cooked fillets from Control, BSFL5% and BSFL10% fed Atlantic salmon. The CA was performed on the sum of scores given by all consumers to each term for describing each sample (RATA scoring). Sensory attributes ordered by sensory dimension: A - appearance, O – odor, Tx – texture and T – taste).

non-trained panelists in Atlantic salmon where partial or total replacement of dietary FM with BSFL did not impair the physico-chemical quality of the fillet (Bruni *et al.*, 2020a; Lock et al., 2016). Moreover, Bruni et al. (2020) found a high percentage of consumers 'liking' and willing to purchase salmon fed with BSFL-based diets as indicated in a blind product test (Bruni *et al.*, 2020a). Despite the positivity in the responses obtained in previous studies, it could be noted that salmon fillet from the group fed BSFL at 10% in the current study were associated with notable rancid odor and metallic taste when compared to control diet. A similar association of dietary BSFL meal with fillet rancidity was mentioned in previously reported study in Atlantic salmon (Belghit et al., 2019) and rainbow trout (Borgogno et al., 2017). Furthermore, according to Bruni *et al.* (2020a), the sensory evaluation scores of odors and flavor were lower for salmon group with 66% replacement of fish meal with BSFL compared to control group. In general, the volatile and non-volatile compounds are responsible for the characteristic flavor of fish particularly taste (amino acids, nucleotides, sugars and mineral salts) and aroma/odor (trimethylamine and dimethylamine). These compounds are produced as a result of oxidation of polyunsaturated fatty acids (Kawai, 1996; Durnford & Shahidi 1998). Therefore, any modification in the fillet fatty acid profile can directly influence the flavor volatile compound of the fillet (Turchini et al., 2009). In the current study, the fillet fatty acid profile was modified due to the dietary inclusion of BSFL meal, which may have contributed to the off flavor in BSFL fed salmon fillet. However, in other feeding trials, the fillet sensory attributes of salmonids were not affected by dietary inclusion of BSFL meal in the diets (Lock et al., 2016; Sealey et al., 2011). Altogether, based on the present trial and earlier published results, marginal changes were observed on the fillet sensory analysis, mostly related to the rancid odor in the fillet of salmonids fed dietary BSFL meal. So far, little information is available on the potential modification of the flavor and aroma compounds in the fillets of farmed salmon in open sea cages fed dietary insect meal and requires further studies in future.

5. Conclusions

The present study shows that Atlantic salmon reared under large scale trial can be fed diets containing up to 10% BSFL meal for the whole sea water phase without affecting the physical and chemical fillet quality between salmon fed control and BSFL-based diets. In our study, dietary modifications had only marginal effects on certain fatty acids within the saturated fatty acid, while no major modifications for the

total monounsaturated and polyunsaturated fatty acids. The EPA+DHA levels were stable in the salmon fillet across all the dietary treatments, while the changes in nutritional indices and sensory properties were associated with inclusion of BSFL in the diets of salmon. Furthermore, inclusion of BSFL meal in the diets of salmon lead to reduction of arsenic levels in the fillets. Overall, the use of insect derived products can be a viable alternative protein source for aquafeed. Thus, the upscaling and commercialization of insect-based feed can pave a way for sustainable feed ingredients in the coming years.

CRediT authorship contribution statement

Philip Antony Jesu Prabhu: Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Radhakrishnan Gopika:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Lock Erik-Jan:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Caimi Christian:** Writing – review & editing, Methodology, Investigation. **Nina S. Liland:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation. **Araujo Pedro:** Writing – review & editing, Investigation, Formal analysis. **Cunha Luís Miguel:** Writing – review & editing, Methodology, Formal analysis. **Rocha Celia:** Writing – review & editing, Investigation, Formal analysis. **Belghit Ikram:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gasco Laura:** Writing – review & editing, Methodology, Investigation, Formal analysis.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.aqrep.2024.101966.

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