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Effect of black soldier fly larvae protein on the texture of meat analogues

Lucian Miron [a], Giuseppe Montevecchi [b,*], Laura Ioana Macavei [b], Lara Maistrello [b], Andrea Antonelli [b], Menno Thomas [a]

[a] Zetadec BV, Nudepark 73A, 6702 DZ, Wageningen, the Netherlands
[b] Department of Life Sciences (Agro-Food Science Area), BIOGEST - SITEIA Interdepartmental Centre, University of Modena and Reggio Emilia, Piazzale Europa 1, 42124, Reggio Emilia, Italy

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ABSTRACT

Black soldier fly larvae are considered an alternative source of protein due to their high protein content and low environmental impact of farming. The effect of incorporation of black soldier fly larvae protein (87.6 ± 2.4 g/100 g content) on meat analogues textural characteristics was determined and compared with those of meat analogues prepared with other alternative sources of protein such as soy protein isolate and vital wheat gluten, while beef round, chicken breast, and a commercial plant-based meat analogue were used as reference matrices. Textural characteristics of the experimental meat analogues were used as response variables in robust regression models ($R^2 > 0.96$) built to determine the main effects and interactions of proteins. Black soldier fly larvae protein decreased the textural characteristics of meat analogues as its amount in the formulation increased. The interaction of black soldier fly larvae protein with soy protein affected the hardness and chewiness of meat analogues, whereas the interaction with wheat gluten only affected their cohesiveness. Black soldier fly larvae protein can partially replace traditional proteins in meat analogues. The optimal incorporations of black soldier fly larvae protein in meat analogues which mimics textural characteristics of chicken breast and plant-based meat analogues were 6.7 g/100 g and 21.5 g/100 g, respectively.

1. Introduction

The global population is projected to rise to 9 billion people by 2050 hence increasing the demand for agricultural production (FAO, 2009), especially animal proteins. However, conventional meat production is not a sustainable source of protein, instead, it contributes significantly to a highly impacting environmental footprint (Steinfeld et al., 2006) and it is also associated with a high level of greenhouse emissions (Tilman & Clark, 2014). Thus, novel and environmentally friendly protein sources such as algae (Chew et al., 2017) and insects (Melgar-Lalanne, Hernández-Álvarez, & Salinas-Castro, 2019) can be an alternative source of proteins.

Black soldier fly larvae (BSFL) are emerging as an alternative source of proteins due to their ability to convert low-value organic resources (e.g., food waste and pig manure, poultry manure) into protein-based and fat-rich biomass suitable for various purposes (Barbi et al., 2020; Bortolini et al., 2020; Gligorescu et al., 2022). The rearing of BSFL is more environmentally friendly compared with conventional livestock because of reduced greenhouse gas emissions, water pollution, and land use (Kouřimská & Adámková, 2016). Moreover, BSFL contain approximately 42–45 g/100 g crude proteins (Diener, Zurbrügg, & Tockner, 2009; Veldkamp & Bosch, 2015; Miron, Postma, Bosch, & Eppink, 2019) which contain all essential amino acids required by humans (Montevecchi, Licciardello, Masino, Miron, & Antonelli, 2021). Thus, BSFL represent a suitable protein source for the food and animal feed industry (Smetana, Palanisamy, Mathys, & Heinz, 2016; Barragan-Fonseca, Dicke, & van Loon, 2017).

Despite these benefits, the use of BSFL for human consumption is challenging because consumers' acceptance remains one of the largest barriers to the commercialization of BSFL as a food source (Bessa, Pieterse, Marais, & Hoffman, 2020). Western consumers are reluctant to eat insects and often associate this practice with feelings of disgust and primitive behavior (van Huis et al., 2013). However, some studies have shown a greater acceptance of foods in which insects are incorporated as processed ingredients rather than presented as whole insects (House, 2016). Thus, the incorporation of insect protein in food products such as meat analogues (MA) is a promising alternative to increase the acceptability of insect protein by consumers while reducing the environmental

* Corresponding author.
E-mail address: giuseppe.montevecchi@unimore.it (G. Montevecchi).

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impact of the food sector (Smetana et al., 2018).

MA, also called meat substitute, mock meat, *faux* meat, or imitation meat, are a class of food products that may resemble meat products in terms of texture, taste, appearance, and smell and/or chemical characteristics of specific types of meat (Joshi & Kumar, 2015). The ingredients used in MA such as wheat gluten, soy protein, mushrooms, rice, leguminous (pulses) protein, algal proteins (Jones, 2016), and insect proteins (Azzollini, Wibisaphira, Lakemond, & Fogliano, 2019) are processed with fat/oil and flavorings to produce a product that tastes like meat or seafood (Kyriakopoulou, Dekkers, & van der Goot, 2019). MA is commonly produced by various techniques such as extrusion, wet spinning, electrospinning, freeze structuring, shear cell technology, and mixing of proteins and hydrocolloids (Dekkers, Boom, & van der Goot, 2018).

The most common process to produce MA is high moisture extrusion (HME) technology (Smetana et al., 2018). In this extrusion process, the raw materials are exposed to thermomechanical stresses due to the shearing and heating of the barrel which affects the raw material properties in terms of protein denaturation and rheological parameters. These changes have a large influence on the MA texture, and this plays an important role in consumers' acceptance (Beniwal, Singh, Kaur, Hardacre, & Singh, 2021). In addition, textural characteristics are known to have a good correlation with sensory attributes (Szczesniak, 2002). Understanding how the rheological properties of BSFL protein affect the texture of MA helps to scale up, design the manufacturing process, and control the product properties (Lin, Huff, & Hsieh, 2000).

The goal of this study was to determine the influence of the incorporation of black soldier fly protein on the textural characteristics of meat analogues with high moisture content (produced by a high moisture extrusion process using a capillary rheometer as a model extruder) in comparison with meat analogues prepared using other alternative sources of protein such as soy protein isolate and vital wheat gluten. Beef round, chicken breast, and a commercial plant-based meat analogue were used as references matrices.

2. Materials and methods

2.1. Materials

Soy protein isolate (SPI) was purchased from Myprotein (Northwich, Cheshire, England). Vital wheat gluten (VWG) was obtained from Cargill (Bergen op Zoom, The Netherlands). Bovine serum albumin (BSA), hexane, potassium metabisulfite ($K_2S_2O_5$), sodium dodecyl sulfate (SDS), sodium hydroxide (NaOH), and tris(hydroxymethyl)aminomethane (TRIS) were purchased from Fischer Scientific (Landsmeer, The Netherlands). The reagents A and B for protein assay were purchased from Bio-Rad Laboratories (Lunteren, The Netherlands).

The BSFL were provided by the University of Modena and Reggio Emilia, Italy. BSFL were reared on canteen kitchen leftovers (CirFood, area Emilia ovest, Reggio Emilia, Italy). The larvae rearing was performed in a climate chamber at 27.0 ± 0.5 °C and 70 ± 10% RH. At the end of the experiment, when the insects reached the desired developmental stage, larvae were cleaned and stabilized through heat as described by Hadj Saadoun et al. (2020). Therefore, the BSFL were frozen (−20 °C) and sent by courier to Zetadec (Wageningen, The Netherlands).

Chicken breast, beef round, and a commercial plant-based meat analogue (Garden Gourmet, Nestlé) were purchased from a local supermarket. Milli-Q water was obtained through a Barnstead Smart2Pure water purification system (Thermo Fischer Scientific, Landsmeer, The Netherlands).

2.2. Extraction of black soldier fly larvae protein (BSFLP)

Fig. 1 shows an overview of the sequential extraction of lipid and protein from BSFL. First, BSFL were freeze-dried and then ground using a Retsch mill (Verder Scientific, Haan, Germany) over a sieve size of 4 mm. The ground sample was used for lipid extraction by Soxhlet with hexane for 18 h at 80 °C. Once the extraction was finished, the lipid

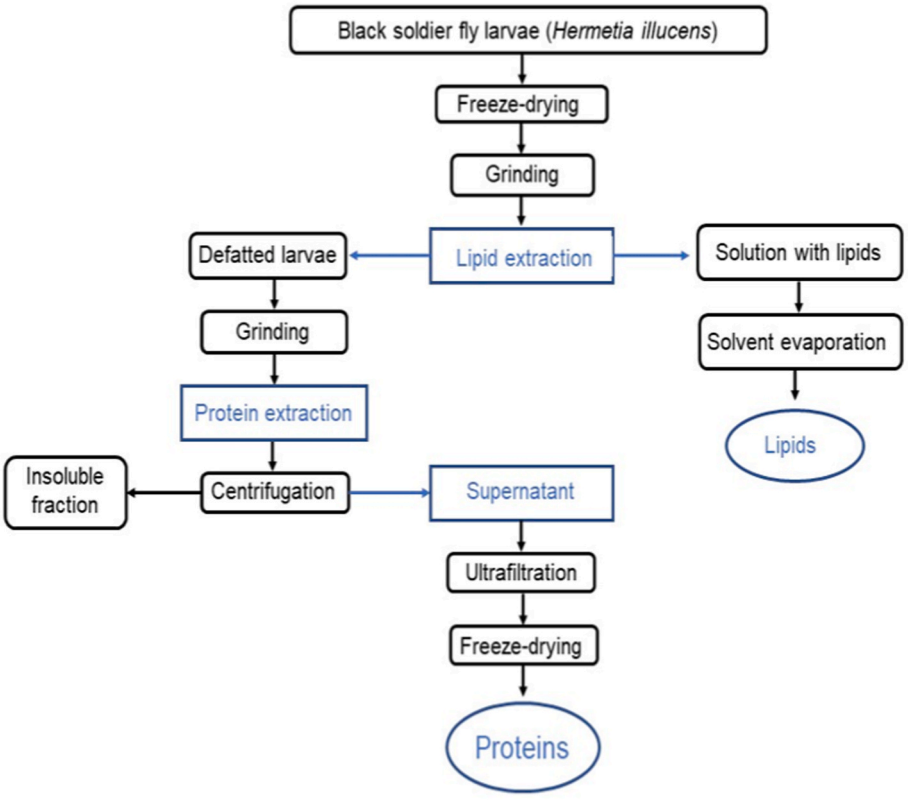

Fig. 1. Schematic representation of proteins' extraction from black soldier fly larvae (*Hermetia illucens*).

fraction was kept in an oven for 6 h at 50 °C to evaporate the solvent. Defatted larvae were ground and sifted using a 0.2-mm sieve size.

An aliquot (200 g) of defatted and finely powdered larvae were dispersed in 2000 mL milli-Q water and the pH was adjusted to 12 using 1 mol/L NaOH. One hundred mL potassium metabisulfite (10 mmol/L) was added to prevent browning. The mixture was stirred on a magnetic stirrer for 2 h at room temperature. This was followed by centrifugation at 2655 RCF × *g* for 30 min. Afterward, the supernatant was subjected to ultrafiltration for 4 h using an Amicon Stirred Cell (Merck Millipore, Burlington, Massachusetts, United States) and an Ultracel membrane (Merck Millipore, Burlington, Massachusetts, United States) with a molecular weight cut-off of 3 kDa. The sample was then freeze-dried and kept in the fridge at +4 °C for further analysis.

2.3. Protein content determination

The Lowry BioRad DC™ protein assay (Bio-Rad Laboratories, Philadelphia, United States) was used to determine the protein content on the dry matter basis of BSFL freeze-dried extract. Thus, 6 mg of freeze-dried BSFLP were added to 1 mL of lysis buffer I (60 mmol/L Tris pH 9, 2 g/100 g SDS) in Eppendorf tubes. The Eppendorf tubes were mixed by a Retsch Vortex Mix (Verder Scientific, Haan, Germany) for 1 min. The samples were incubated at 100 °C for 30 min, followed by centrifugation for 10 min at 1301 RCF × *g*. Then, the supernatant was diluted 10 times with milli-Q water and 100 μL of diluted supernatant were added to a test tube to which 0.5 mL reagent A and 4 mL reagent B were added. The protein quantification was performed using bovine serum albumin as a protein standard. Absorbance was measured after 15 min at 750 nm using a spectrophotometer (Buck Scientific Cecil, Norwalk, United States). The assay was performed in triplicate.

The protein content was calculated according to equation (1):

$$Protein\ content(g\ /\ 100\ g) = \frac{mass\ protein\ sample}{mass\ freeze\ dried\ sample} \cdot 100 \quad (1)$$

2.4. Preparation of the experimental mixtures

Fig. 2 shows the three-component mixture design (Cornell, 1981) used to produce MA samples. The quantities of water (55 g/100 g) and sunflower oil (5 g/100 g) remain constant, while the remaining part (40 g/100 g) was variable and consisted of soy protein isolate (SPI, X_1), vital wheat gluten (VWG, X_2), and BSFLP (X_3) (see Table 1).

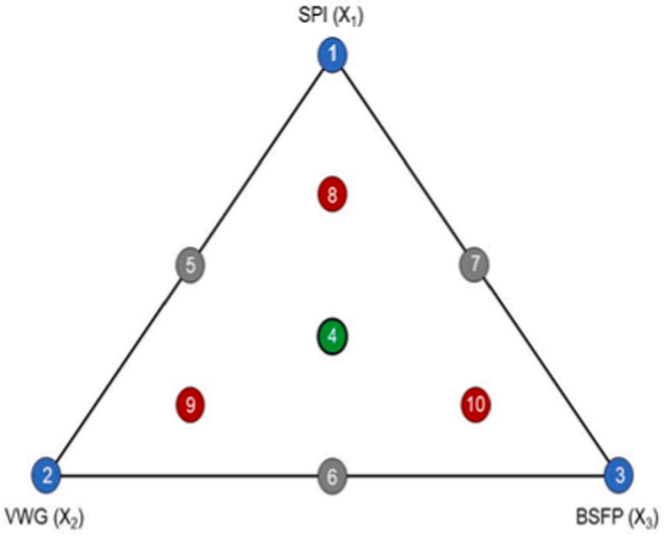

Fig. 2. Mixture design used to determine functional characteristics of soy protein isolate (SPI, X_1), vital wheat gluten (VWG, X_2), and black soldier fly larvae protein (BSFP, X_3) in meat analogues.

The ingredients were blended in a food processor (Kenwood Chef Premier, Woking, United Kingdom) to a total weight of 100 g per batch. The proportions of each ingredient were expressed as fractions of the mixture to a total of one ($X_1 + X_2 + X_3 = 1$). The representation of the ten mixtures (see Fig. 2) consisted of three single ingredient treatments (points 1, 2, and 3; in blue), three two-ingredient mixtures (points 5, 6, and 7; in gray), and four three-ingredient mixtures (points 4, 8, 9, and 10; in red and green). The central point (4; in green) was replicated three times to obtain a measure of the experimental error.

2.5. Capillary rheometer

Test formulations were extruded in a capillary rheometer (Instron SR50, Norwood, Massachusetts, United States), collected, and shaped into a rod-shaped disc which was used as a basis for further texture profile analysis.

A sample representing each formulation (100 g) of the mixture design was loaded in the barrel of the capillary rheometer, allowed to equilibrate the temperature for 5 min, and extruded at 100 °C. The formulations were extruded through a capillary die of 20 mm length and 1 mm diameter at a shear rate of 500 (1/s).

The molten material was directly collected into a pre-heated and thermally regulated single compression cell and shaped into a rod-shaped disc (55 mm diameter, the height dependent on the formulation) by compression with 500 N at 100 °C for 15 min using a Universal Testing Machine (Instron 3366, Norwood, Massachusetts, United States). The samples were stored at 4 °C for further analyses.

2.6. Texture profile analysis (TPA)

MA samples were evaluated by TPA which is a test that compresses a bite-size piece of food two times in a reciprocating motion that imitates the action of a jaw (Szczesniak, 1963). A Universal Testing Machine (Instron 3366, Norwood, Massachusetts, United States) was used to determine the textural characteristics of the experimental meat analogues, in terms of hardness, cohesiveness, springiness, and chewiness, by applying the TPA (Bourne, 2002). The compression was 50% of the sample height with no delay between first and second compression. The speed of the crosshead was 50 mm/min. Ten specimens of each treatment were analyzed by repeating the protocol using the same parameters. The texture parameters were calculated according to Bourne (1968), except for springiness which was calculated according to the method described by Fiszman Pons & Damásio (1998).

Table 1
Experimental portion (40 g/100 g) of the mixture composition of meat analogues formulated with soy protein isolate (SPI), vital wheat gluten (VWG), and black soldier fly larvae protein (BSFLP) in a mixture design. The remaining portion (60 g/100 g) is constant and consists of water (55 g/100 g) and sunflower oil (5 g/100 g).

Formulation	Ingredients' proportion[a]		
	SPI[b] (X_1)	VWG[c] (X_2)	BSFLP[d] (X_3)
1	1.000	–	–
2	–	1.000	–
3	–	–	1.0000
4[e]	0.333	0.333	0.333
5	0.500	0.500	–
6	–	0.500	0.500
7	0.500	–	0.500
8	0.667	0.167	0.167
9	0.167	0.667	0.167
10	0.167	0.167	0.667

[a] Formulation numbers correspond to Fig. 2.
[b] SPI – Soy protein isolate.
[c] VWG – Vital wheat gluten.
[d] BSFLP – Black soldier fly larvae protein.
[e] 3 repetitions in the central point were performed.

Table 2
Predicted models for meat analogues obtained by mixture design with 3 components.

Variable	Dependent variable			
	Hardness	Cohesiveness	Springiness	Chewiness
SPI	22.020***	0.491***	0.599***	6.326***
VWG	7.427**	0.602***	0.641***	3.035***
BSFLP	4.102	0.057	0.012	0.379
SPI × VWG	−2.067	−0.242		−2.109
SPI × BSFLP	−42.331***	−0.341		−14.022***
VWG × BSFLP	−7.871	−0.617***		−7.133**
R^2	0.966	0.994	0.993	0.971
Adjusted R^2	0.931	0.987	0.990	0.942
Residual Std. Error	2.499	0.038	0.044	0.628
F_{value}	28.040***	158.325***	417.093***	33.428***

Note: *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

Rod-shaped discs of the three references matrices (beef round, chicken breast, and the commercial plant-based meat analogue) were boiled at 100 °C for 10 min as proposed by Choi et al. (2016) and then cut into 5.00 ± 0.02 mm cubes for TPA.

2.7. Statistical analysis and modeling of experimental data

Regression analysis was performed to evaluate the formulations and the effects of the ingredients on the textural characteristics. A polynomial equation of function x_i was fitted for each variable assessed at each experimental point. This polynomial model differs from full polynomial models because it does not contain a constant term (intercept equal to zero). The polynomial model equation (2) is:

$$Y_i = \beta_{i1}X_1 + \beta_{i2}X_2 + \beta_{i3}X_3 + \beta_{i12}X_1X_2 + \beta_{i13}X_1X_3 + \beta_{i23}X_2X_3 \quad (2)$$

Where:

Y_i – textural characteristic (hardness, cohesiveness, springiness, or chewiness)

X_1 – SPI

X_2 – VWG

X_3 – BSFLP

β_1, β_2, β_3 – linear coefficients

β_{12}, β_{13}, β_{23} – second order interaction

A full model was fitted for each textural characteristic and non-significant higher-order interactions were removed from the model based on analysis of variance.

Ternary contour plots representing the model outcome of each textural characteristic were generated using R statistical language and environment (R Development Core Team, 2009) in the package 'mixexp' (Lawson, Wilden, & Piepel, 2016). Results are presented as a mean of ten specimens tested per formulation.

3. Results and discussion

The protein content of the BSFLP freeze-dried extract quantified by Lowry assay was 87.6 ± 2.4 g/100 g (w/w). Table 2 shows the calculated regression coefficients (R^2, adjusted R^2, residual standard errors, corresponding F-values, and *p*-values) of the samples prepared through the mixture design. The values of hardness, cohesiveness, and chewiness were modeled with a second-order interaction model, whereas springiness fitted better to a linear model.

The accuracy of models was estimated using the coefficients of determination (R^2 and adjusted R^2 values). The values of R^2 for hardness, cohesiveness, springiness, and chewiness were 0.966, 0.994, 0.993, and 0.971; whereas adjusted R^2 for hardness, cohesiveness, springiness, and chewiness were 0.931, 0.987, 0.990, and 0.942, respectively. Because for a good fit of a model, R^2 should be at least 0.80 (Colin Cameron & Windmeijer, 1997), all coefficients complied with this rule.

Fig. 3 shows the isocontour plots derived from the statistical models of hardness, cohesiveness, springiness, and chewiness. Hardness is defined as the maximum force of the first compression (Bourne, 2002). Table 2 shows that the hardness of MA was affected by SPI ($p < 0.01$) and VWG ($p < 0.05$), whereas BSFLP did not show a significant effect ($p > 0.1$) on the hardness of samples. Concerning the interaction between components, only the interaction SPI × BSFLP affected ($p < 0.01$) the hardness of samples. The isocontour plot of hardness ranged between 0 and 20 N. Increasing the SPI in the mixture increases the hardness of MA, whereas, increasing the BSFLP in the mixture resulted in lower hardness of MA (Fig. 3a).

Cohesiveness is defined as the extent to which a material can be deformed before it ruptures. Cohesiveness is also the strength of internal bonds making up the body of the product (Szczesniak, 1991). Fig. 3b shows the effects of the independent variables on the cohesiveness of MA. Table 2 shows that the cohesiveness of MA was affected by SPI and VWG (both $p < 0.01$), and by the interaction VWG × BSFLP ($p < 0.01$). The isocontour plot of cohesiveness ranged between 0 and 0.55. Thus, increasing the SPI and VWG in the mixture significantly increased the cohesiveness of MA, whereas, increasing the BSFLP in the mixture resulted in lower cohesiveness of MA. The highest values of cohesiveness were obtained at the highest levels of VWG in the mixture.

Springiness is defined as the rate at which a deformed material goes back to its unreformed condition after the deforming force is removed (Szczesniak, 1991). Table 2 shows that the springiness of MA was affected by SPI and VWG (both $p < 0.01$), while BSFLP did not have a significant effect ($p > 0.1$) on springiness.

Springiness ranged between 0.1 and 0.6 (Fig. 3c). Increasing the SPI and VWG in the mixture significantly increased the springiness of MA, whereas increasing the BSFLP in the mixture resulted in lower springiness (Fig. 3c).

Chewiness is defined as the energy required to masticate a solid product until it is ready to be swallowed (Szczesniak, 1991). Chewiness ranged between 0 and 6 N (Fig. 4d). The isocontour plot of chewiness indicates that by increasing the SPI in the mixture, the chewiness of MA also significantly increases, whereas, by increasing the BSFLP in the mixture, the chewiness of MA decreases. The chewiness of MA was affected by SPI ($p < 0.01$) and VWG ($p < 0.01$) (Table 2). Chewiness was also influenced by the interactions SPI × BSFLP ($p < 0.01$) and VWG × BSFLP ($p < 0.05$). On the other hand, the chewiness of samples was not affected by BSFLP and by the interaction SPI × VWG ($p > 0.1$) (Table 2). Chewiness follows the same trend as hardness because it is hardness-related, according to the definition given by Bourne (2002).

The textural characteristics of three reference matrices: beef round, chicken breast, and plant-based meat analogue were also determined (Fig. 4). The beef round had a hardness mean value of 25.70 N, higher than all mixtures tested in the present study. The mean hardness values of chicken breast and plant-based meat analogue were observed to encompass the hardness values obtained with the mixture design of MA tested. Thus, chicken breast had a mean value of hardness of 17.24 N and plant-based meat analogue had a mean hardness of 9.75 N.

Fig. 4b shows the cohesiveness values of reference samples. The mean cohesiveness values of beef round, chicken breast, and plant-based meat analogue were 0.40, 0.42, and 0.35, respectively. The mean springiness values of beef round, chicken breast, and plant-based meat analogue were 0.50, 0.52, and 0.46 (see Fig. 4c). Lastly, the mean chewiness values of beef round, chicken breast, and plant-based meat analogue were 4.93 N, 3.96 N, and 1.65 N.

The experimental values of cohesiveness, springiness, and chewiness obtained with a mixture of SPI, VWG, and BSFLP encompass the range of texture properties as obtained for reference samples namely beef round, chicken breast, and plant-based meat analogue.

However, based on the results of hardness, cohesiveness, springiness, and chewiness can be observed that the textural chracteristics of reference samples cannot only be mimicked using BSFLP as a single ingredient. The textural values obtained with BSFLP as a single ingredient

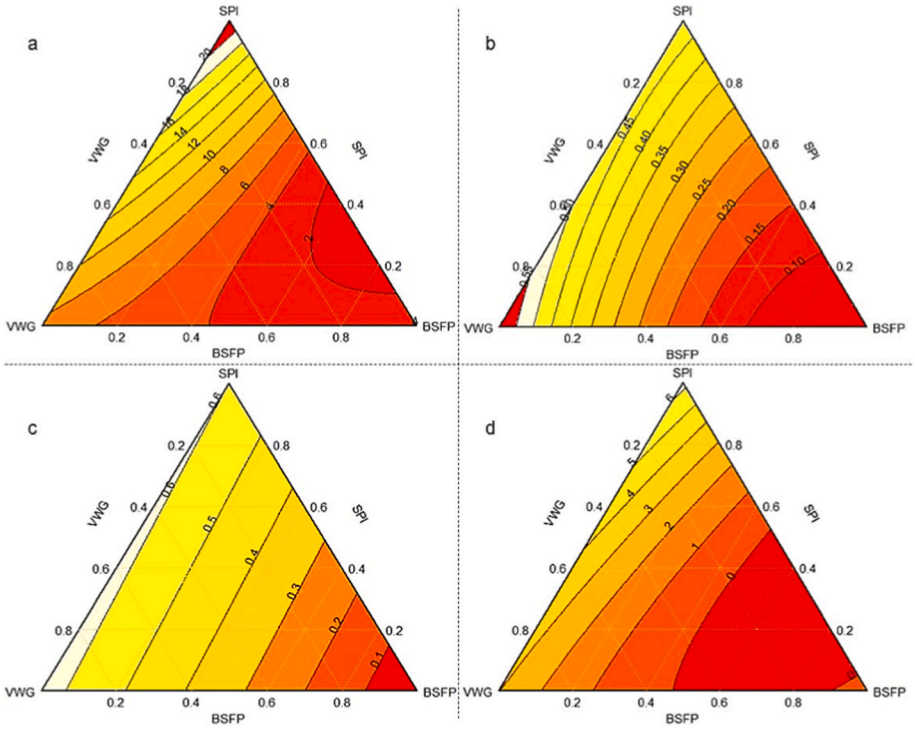

Fig. 3. Isocontour plots for (a) hardness (N), (b) cohesiveness, (c) springiness and (d) chewiness (N) of meat analogues formulated with soy protein isolate (SPI), vital wheat gluten (VWG), and black soldier fly larvae protein (BSFP).

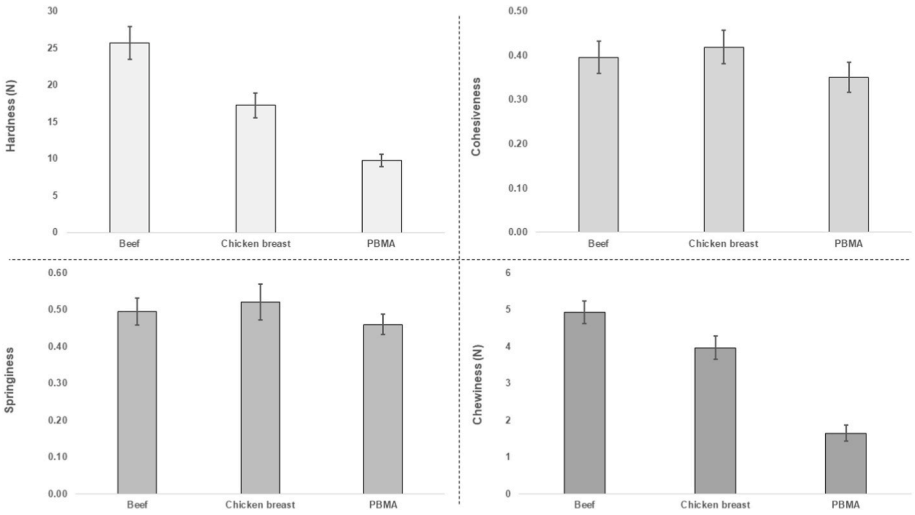

Fig. 4. Hardness (a), cohesiveness (b), springiness (c), and chewiness (d) of three reference samples. PBMA: plant-based meat analogue.

were much lower than the textural values of beef round, chicken breast, and plant-based meat analogues. Thus, in order to mimic the textural characteristics of reference samples, BSFLP can only be used as part of a formulation, in blends with SPI and VWG.

From the texture results, SPI seems to be the component with the highest effect on hardness, cohesiveness, springiness, and chewiness values. The SPI showed an elastic behavior which reflects in chewable, rubber-like texture of MA. The same behavior of SPI has also been shown by Wittek, Zeiler, Karbstein, and Emin (2020) and can be explained by a combination of hydrophobic interactions, hydrogen bonds, disulfide bonds, and their interactions occurring during the high moisture extrusion of SPI which plays a significant role in the structure formation of products (Chen, Chen, Ren & Zhao., 2011).

In our study, the cohesiveness and springiness values increase by increasing the VWG in MA formulation. This behavior can be explained by the formation of disulfide bonds and covalent bonds on wheat gluten during the extrusion process at high water content (54 g/100 g) as shown by Pietsch, Karbstein, and Emin (2018). As also discussed by Guerrieri, Alberti, Lavelli, and Cerletti (1996), temperatures above 75 °C the heat-induced polymerization reactions of wheat gluten are initiated. In turn, this change in molecular structure increases the strength of internal bonds resulting in an increased cohesiveness of samples.

From our results, it can be concluded that BSFLP reduces the textural characteristics as observed from the TPA analysis compared to VWG and SPI. However, BSFLP can be used in MA as a protein alternative due to its low environmental impact and nutritional value. Other authors have shown that BSFLP displayed no gelling behavior upon heating (Janssen, 2018) most likely because these proteins do not have enough

crosslinking, hydrophobic interactions, or hydrogen bonds to form a three-dimensional network (Onwulata & Qi, 2006). This behavior influences the textural characteristics of MA, as observed in our study by the overall lower TPA values compared with SPI and VWG. Other authors have also found the same behavior in another protein source such as pea protein isolate (Osen, Toelstede, Wild, Eisner, & Schweiggert-Weisz, 2014). Hence, the difference in functionalities influenced the viscosity of the proteins during extrusion which, in turn, affected the textural characteristics of the products.

The extraction conditions can influence the quality and functionality of protein as shown by Zhao, Vázquez-Gutiérrez, Johansson, Landberg, and Langton (2016). However, in the case of BSFLP, other extraction conditions used by Janssen (2018) result in BSFLP exhibiting no gelling behavior upon heating. Therefore, it is not expected that other extraction conditions will change the results of the present study.

The main goal of this study was to determine the effect of BSFLP on the textural characteristics of MA. Moreover, the optimal amounts of BSFLP necessary in MA formulations that mimic the textural characteristics of three reference samples were also determined. The textural characteristics of beef round could not be mimicked because the hardness of beef round was higher than the maximum hardness values of MA formulated using SPI, VWG, and BSFLP. On the other hand, the texture of chicken breast and plant-based meat analogue can be mimicked because the textural characteristics of the reference samples are within the observed range of the protein mixtures used in the mixture design used in this study. Hence, the optimal amount of BSFLP needed in the formulation of MA to closely mimic the textural characteristics of chicken breast was 6.7 g/100 g, the remaining fraction being 74.4 g/100 g SPI and 18.9 g/100 g VWG. To closely mimic the textural characteristics of plant-based meat analogue, the optimal amount of BSFLP needed in the formulation of MA was 21.5 g/100 g with 53.5 g/100 g SPI and 25.0 g/100 g VWG making up the rest of the optimal formulation.

4. Conclusions

In this study, the effect of BSFLP on the texture of MA was achieved by employing a mixture design. The BSFLP was first extracted and showed a protein content of 87.6 ± 2.4 g/100 g.

The textural characteristics (hardness, cohesiveness, springiness, and chewiness) of the experimental MA decreased by increasing the amount of BSFLP in MA sample formulation. The interaction of BSFLP with SPI affected the hardness and chewiness of MA samples, while the interaction of BSFLP with VWG affected the cohesiveness of MA samples. The optimal formulation which closely mimics the textural characteristics of chicken breast was 74.4 g/100 g SPI, 18.9 g/100 g VWG, and 6.7 g/100 g BSFLP. The optimal formulation which closely mimics the textural characteristics of plant-based meat analogue was 53.5 g/100 g SPI, 25.0 g/100 g VWG, and 21.5 g/100 g BSFLP.

The development of MA with alternative proteins such as BSFLP helps broaden the applicability of insect proteins in the food industry. This study demonstrated that MA made from insect proteins in combination with vegetable proteins can provide similar textural characteristics to those of chicken breast and commercial plant-based meat analogues. Understanding the structural changes during processing could help optimize the reaction conditions of individual ingredients and their interactions to obtain MA with desirable textural characteristics.

Despite all promising information about BSFLP, Western societies are reluctant to consume insects. Thus, the usa of insect-protein fractions as a food ingredient, instead of whole insects, can be a powerful strategy to encourage the consumption of alternative insect-derived proteins. Since MA are usually consumed by flexitarians and vegetarians, this group of consumers may be the early adopters of insect proteins and be targeted as possible trendsetters.

CRediT authorship contribution statement

Lucian Miron: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, preparation. **Giuseppe Montevecchi:** Conceptualization, Validation, Investigation, Data curation, Writing – review & editing. **Laura Ioana Macavei:** Formal analysis. **Lara Maistrello:** Supervision, Funding acquisition. **Andrea Antonelli:** Supervision, Project administration, Funding acquisition. **Menno Thomas:** Writing – review & editing, Supervision, Funding acquisition, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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