Studii şi Cercetări Ştiinţifice
Chimie şi Inginerie Chimică, Biotehnologii, Industrie Alimentară

Scientific Study & Research
Chemistry & Chemical Engineering, Biotechnology, Food Industry

2026, **27** (2), pp. 139 – 152
https://doi.org/10.29081/ChIBA.2026.662
ISSN 1582-540X

ORIGINAL RESEARCH PAPER

PHYSICOCHEMICAL, OXIDATIVE, AND SENSORY PROPERTIES OF BAKED PORK MEATBALLS FORMULATED WITH CRICKET POWDER AND SPIRULINA AS ALTERNATIVE PROTEINS

Maria M. Momchilova[1*], Dilyana N. Gradinarska-Ivanova[2], Petya B. Boyanova[3], Katya I. Valkova-Yorgova[2]

[1]Institute of Food Preservation and Quality, Food Technology Division, Agricultural Academy of Bulgaria, 154 Vasil Aprilov Blvd., 4000 Plovdiv, Bulgaria
[2]University of Food Technologies, Technological Faculty, Department of Meat and Fish Technology, 26 Maritsa Blvd., 4002 Plovdiv, Bulgaria
[3]University of Food Technologies, Technological Faculty, Department of Milk and Dairy Products, 26 Maritsa Blvd., 4002 Plovdiv, Bulgaria

*Corresponding author: masha821982@abv.bg

Received: November, 19, 2025
Accepted: May, 18, 2026

Abstract: This study examined the effects of replacing soy protein with cricket powder and spirulina on the compositional, technological, oxidative, and sensory properties of baked pork meatballs. Seven formulations were prepared with varying proportions and combinations of protein sources: soy protein, spirulina, and cricket powder. The inclusion of these alternative proteins significantly influenced the proximate composition, color, emulsion stability, and texture of the products ($P < 0.05$). Samples containing cricket powder exhibited higher protein and lipid contents but lower moisture and cooking yield, indicating stronger protein denaturation and reduced water-holding capacity during heat treatment. The addition of spirulina improved the nutritional profile through increased mineral and fiber content and enhanced oxidative stability due to its phycocyanin and carotenoid pigments. The combined use of spirulina and cricket powder increased protein content and textural firmness while maintaining satisfactory emulsion stability. The lowest thiobarbituric acid reactive substances (TBARS) values (0.31 - 0.41 mg MDA·kg^{-1}) and the highest DPPH activity (up to 144 μmol TE/100 g) were recorded in cricket-enriched samples. Sensory evaluation confirmed good overall acceptability, although spirulina inclusion affected color perception. The findings demonstrate the functional potential of cricket powder and spirulina as sustainable protein ingredients that can partially substitute soy protein in thermally processed meat products.

Keywords: *antioxidants, emulsion stability, lipid oxidation, protein substitution, sensory analysis, texture*

INTRODUCTION

In recent years, there has been growing interest in foods with high nutritional and functional value that align with the principles of sustainable production. Meat and meat products are traditionally regarded as valuable sources of high-quality proteins, B-group vitamins, minerals, and bioactive compounds [1 – 3]. At the same time, their high content of saturated fatty acids and cholesterol has been associated with adverse effects on cardiovascular health. Reducing their consumption leads to an approximately 21 % decrease in the risk of cardiovascular diseases, including heart attack and stroke [4].

In response to the growing demand for the development of healthier, more environmentally friendly, and economically efficient food products, increasing attention has been directed toward alternative protein sources. These approaches aim not only to reduce the environmental footprint and production costs of meat products but also to preserve their nutritional quality, safety, and positive consumer perception. Among these alternatives, soy protein preparations are the most widely used in the meat industry due to their high protein content, balanced amino acid profile, and favorable fatty acid composition [5, 6]. However, soy production is associated with a considerable environmental impact, including intensive land use and greenhouse gas emissions, while soy proteins are also characterized by pronounced allergenicity [7]. This highlights the need to identify sustainable and safe alternatives with comparable technological and functional properties.

Due to their high biotechnological potential for rapid biomass accumulation, efficient resource utilization, and significantly lower environmental requirements for producing a unit of protein compared to soy and meat, microalgae and edible insects are emerging as innovative, sustainable unconventional protein sources. Spirulina (*Arthrospira platensis*) is characterized by a high-quality protein content (53 - 75 %) along with carbohydrates (15 - 25 %), lipids (~ 7 %), dietary fiber (3 - 6 %), minerals (7 - 13 %), and bioactive compounds such as phycocyanin, chlorophylls; carotenoids, and phenolics responsible for its strong antioxidant capacity [8], while cricket flour (Acheta domesticus) contains approximately 70 % protein, 20 % lipids, 9.5 % dietary fiber (mainly chitin), and very low carbohydrate content (~ 0.5 %), together with micronutrients such as iron and vitamin B12 [9 – 11]. Over the past decade, they have attracted growing interest from both the scientific community and the food industry [12 – 14]. In this regard, it is necessary to achieve a balanced integration of alternative protein sources, such as cricket flour and spirulina, into conventional meat matrices, in order to maximize techno-functional and economic benefits without adversely affecting the sensory characteristics of the product. In this context, there is a need to explore their effective incorporation into conventional meat matrices, particularly through the combined use of spirulina and cricket flour as partial or complete substitutes for soy protein, in order to maximize techno-functional and economic benefits without adversely affecting the consumer acceptability of the developed product. Available data indicate that actual tasting of these protein sources enhances consumer acceptance and increases willingness for future consumption, while repeated exposure helps overcome neophobia or aesthetic aversion and promotes acceptance [15].

Both spirulina and cricket flour have been successfully incorporated into various meat products, including sausages, patties, and fermented products, where they contributed nutritional profiles and oxidative stability, although challenges related to color and sensory perception have been reported [16 – 18].

Meat semi-finished products, particularly meatballs, are among the most widespread and preferred meat products [19], which underscores the need to develop innovative formulations that combine high organoleptic quality with the principles of sustainable production. Previous studies have primarily investigated spirulina and cricket powder individually, as well as in raw or minimally processed systems, while their combined application and behavior during thermal processing remain insufficiently explored. This study aims to evaluate the potential of these protein sources as partial substitutes for soy protein in baked pork meatballs, with particular emphasis on their combined effects on product quality. The novelty of the work lies in assessing their synergistic impact on oxidative stability, texture, and sensory characteristics in thermally processed meat products.

MATERIALS AND METHODS

Sample Preparation

The experiment was conducted using the following basic formulation: lean pork (shoulder) – 500 $g \cdot kg^{-1}$, semi-fat pork – 500 $g \cdot kg^{-1}$, water – 200 $g \cdot kg^{-1}$, soy protein – 10 $g \cdot kg^{-1}$, and sodium chloride – 1.8 $g \cdot kg^{-1}$. Seven sample variants were prepared, differing in the type and quantitative ratio of the protein additives used - soy protein (S), spirulina powder (Sp), and cricket flour (CP) (Table 1). The cricket flour was provided by EntoSynergy Ltd. (Balgarevo, Bulgaria), while the meat raw materials and other additives were purchased from the retail market. The protein additives were pre-hydrated in water at a ratio of 1:3 (w/v).

Table 1. *Formulation of control and experimental baked pork meatballs containing soy protein, spirulina, and cricket powder.*

Sample	Ingredient ratios, [$g \cdot kg^{-1}$]		
	Soy protein (X1)	**Spirulina powder (X2)**	**Cricket powder (X3)**
S	10.0	0.0	0.0
Sp	0.0	10.0	0.0
CP	0.0	0.0	10.0
SSp	5.0	5.0	0.0
SCP	5.0	0.0	5.0
SpCP	0.0	5.0	5.0
SSpCP	3.33	3.33	3.33

The meat was minced using a meat grinder (Maxima Meat Mincer, model, Maxima Kitchen Equipment, The Netherlands) equipped with a 6 mm plate opening, divided into seven equal portions, and mixed with the required additives using a laboratory mixer (COOK-IT kitchen robot, 600 W, COOK-IT, China). Meatballs were shaped from the obtained meat mixture, each with a weight of 0.060 ± 0.005 kg. The samples were baked in an electric oven (Rakhovets, Bulgaria) at 180 ± 2 °C until they reached a core temperature of 72 °C. The internal temperature of the samples was monitored using a digital food thermometer (TP101, SHTROL, China), equipped with a 15 cm stainless steel probe. After cooling to 4 °C, the samples were analyzed according to the presented physicochemical and technological parameters.

Analysis Methodology

Proximate composition of baked pork meatballs

The moisture content (MC) was determined by drying at 104 ± 1 °C to a constant weight using a KERN MLS-A moisture analyzer (Kern & Sohn GmbH, Germany). Protein content was determined by the Kjeldahl method [20], and fat content was determined by the Soxhlet extraction method [21]. Ash and dietary fiber contents were determined according to [22, 23], respectively, while carbohydrate content was calculated by difference, following the methodology in [24]. Sodium chloride content was determined by the Mohr argentometric titration method using 0.1 N $AgNO_3$ (≥ 99.8 % purity; Ridakom Ltd., Bulgaria) was used. and 5 % K_2CrO_4 (analytical grade; Ridakom Ltd., Bulgaria) as an indicator at *p*H 7 - 8. Results are expressed as % NaCl [25].

The energy value was calculated based on the mean values of the components in accordance with Regulation (EU) No 1169/2011. Water activity (aw) was measured using a HygroPalm HP23 (Rotronic AG, Switzerland) at 22 - 25 °C [26].

Measurement of pH and color of baked pork meatballs

The *p*H was measured using a Milwaukee MW102 PRO + 2-in-1 (Milwaukee Instruments, Italy) after extracting of the sample with water at a ratio of 1:9 (w/v). Color parameters (L*, a*, b*, C, and h) were determined spectrophotometrically in the CIE Lab system using a Minolta Chroma Meter CR-410 (Konica Minolta, Osaka, Japan).

Determination of lipid oxidation (TBARS) and antioxidant capacity (DPPH)

The content of thiobarbituric acid reactive substances (TBARS) was determined according to the method described by [27]. The results were expressed as mg malondialdehyde (MDA) per kg of sample. Antioxidant activity was measured by the neutralization of the DPPH radical according to the method of [28] with modification: 250 μL of an aqueous sample extract was mixed with a methanolic DPPH solution (6×10^{-5} M) in a 1:9 (v/v) ratio, followed by incubation in the dark at room temperature for 20 min and absorbance measurement at 515 nm (Evolution 201 UV–Vis Spectrophotometer, Thermo Scientific) [29]. The results are expressed as μmol Trolox equivalents (TE) per 100 g of sample.

Emulsion stability and yield

Emulsion stability (ES) was evaluated according to the method of [30]. Thirty grams of each raw sample was heated in a water bath at 70 °C for 30 min and then centrifuged at 2000 $rot \cdot min^{-1}$ for 10 min. The mass of the released water and fat was used to calculate emulsion stability. Thermal losses were determined by calculating the ratio between the sample mass before and after heat treatment, following the method of [31].

Texture Profile Analysis (TPA)

Texture profile analysis was performed using a TA-XT Plus texture analyzer (Stable Micro Systems, Surrey, UK). The samples had a diameter of 40 ± 2 mm and a height of

25 ± 2 mm. A cylindrical probe with a diameter of 50 mm was used, with a compression speed of 2 $mm \cdot s^{-1}$, deformation of 8 mm, and a 5 s interval between compressions. The determined parameters were hardness, springiness, cohesiveness, gumminess, chewiness, and adhesiveness [32 – 34].

Sensory analysis

The sensory evaluation was carried out on one control and six experimental samples of meatballs. The samples were evaluated according to the following attributes: appearance, color, texture, taste, aroma, aftertaste, saltiness, and overall sensory acceptability. Each sensory attribute was assessed using a structured 9 – point hedonic scale ranging from 1 – dislike extremely; 2 – dislike very much; 3 – dislike moderately; 4 – dislike slightly; 5 – neither like nor dislike; 6 – like slightly; 7 – like moderately; 8 – like very much; and 9 – like extremely [35].

Statistical analysis

All experimental data were analyzed using one-way analysis of variance (ANOVA) with Statgraphics 16 software. Differences between variants were evaluated using Duncan’s post-hoc test at a significance level of $P < 0.05$. All analyses were performed in triplicate, and the results are presented as mean values ± standard deviation (SD).

RESULTS AND DISCUSSION

Proximate composition analysis

The results of the chemical composition analysis of the control and experimental baked meatball samples are presented in Table 2. The obtained values reflect the influence of the incorporated spirulina powder and cricket flour, as substitutes for soy protein on the nutritional and technological profile of the products after thermal processing.

The highest moisture content was recorded in the control sample containing soy protein (S), while samples containing cricket flour showed lower values for this parameter, following the order SCP > CP > SpCP > SSpCP. The reduced moisture content suggests a denser and drier texture in the products. When soy protein was replaced solely with spirulina (sample Sp), the moisture values remained close to those of the control, indicating a similar water-holding capacity. However, in samples with combined inclusion of spirulina, a lower water content was observed, likely due to its limited initial hydration in the mixture and the reduced accessibility of water molecules to its hydrophilic functional groups.

The highest protein content was found in the sample containing both spirulina and cricket flour (SpCP 20.24 %), exceeding the values observed in the control and other variants. This confirms that the combination of the two alternative sources contributes to an improved protein profile. Regarding lipids, the sample with cricket flour (CP) exhibited the highest fat content (15.33 %), attributable to the naturally higher lipid levels in insects [36]. The inclusion of spirulina resulted in lower fat levels but higher contents of dietary fiber and mineral substances, thereby enhancing the nutritional profile of the product. This may contribute to improved digestion, a greater feeling of satiety, and increased bioavailability of microelements such as iron, magnesium, and calcium, which have been reported by numerous authors to occur in significant amounts in spirulina [37, 38]. Despite the presence of sodium and potassium ions in spirulina [39], which may enhance the perception of salty taste, the determined sodium chloride content was similar across all samples. This is because the applied Mohr method measures chloride rather than sodium ions; these measurements are then used to calculate the NaCl content.

Table 2. *Proximate composition (mean ± SD) of baked pork meatballs formulated with soy protein, spirulina, and cricket powder*

Parameter	**Sample**						
	S	**Sp**	**CP**	**SSp**	**SCP**	**SpCP**	**SSpCP**
Moisture [%]	50.73±3.72^{b}	49.50±1.58^{ab}	48.45±0.23^{ab}	48.70±0.21^{ab}	49.09±0.88^{ab}	47.18±2.44^{ab}	44.97±6.23^{a}
Proteins [%]	18.73±1.87^{ab}	16.10±2.68^{ab}	15.34±4.00^{a}	17.45±0.34^{ab}	18.24±1.02^{ab}	20.24±4.48^{b}	17.71±0.12^{ab}
Fats [%]	13.43±0.07^{ab}	14.22±1.31^{ab}	15.33±3.23^{b}	12.39±1.86^{a}	13.87±0.71^{ab}	13.09±0.65^{ab}	12.72±1.30^{ab}
Carbohydrates [%]	0.50±0.03^{a}	0.60±0.14^{a}	0.50±0.03^{a}	0.50±0.03^{a}	0.44±0.14^{a}	0.50±0.03^{a}	0.60±0.14^{a}
Dietary fibers [%]	12.68±1.95^{a}	14.72±1.58^{a}	12.61±2.08^{a}	13.85±0.08^{b}	13.02±1.37^{a}	14.76±1.66^{a}	16.66±4.95^{a}
NaCl [%]	2.59±0.12^{a}	2.69±0.04^{a}	2.71±0.08^{a}	2.66±0.00^{a}	2.74±0.14^{a}	2.66±0.02^{a}	2.59±0.12^{a}
Ash [%]	4.36±0.08^{b}	3.54±0.56^{a}	3.91±0.11^{ab}	4.00±0.27^{ab}	3.97±0.21^{ab}	3.74±0.20^{ab}	3.62±0.39^{ab}
Energy value [kJ·kcal^{-1}]	927/222	937/224	947/227	882/211	943/226	963/231	934/221

Notes: Values are expressed as mean ± standard deviation (n = 3). Different superscript letters within the same column indicate significant differences ($P < 0.05$). S – soy protein (control); Sp – spirulina; CP – cricket powder; SSp – soy + spirulina; SpCP – spirulina + cricket powder; SSpCP – soy + spirulina + cricket powder.

No statistically significant differences were found among the samples regarding carbohydrate content ($P > 0.05$). The lowest energy value was recorded for sample SSp (882 kJ / 211 kcal), while the highest was observed in the samples containing cricket flour (CP) and the combination of cricket flour and spirulina (SpCP), which is logical considering their higher fat and protein contents. The obtained results are consistent with observations from the previous study on raw meatballs [40], as thermal processing led to the expected reduction in moisture and a relative increase in the concentration of dry matter, proteins, and lipids.

*p*H, aw and color analysis

The *p*H values and water activity (a_W) of the examined baked semi-finished products are presented in Table 3. It was found that the samples containing spirulina (Sp) exhibited the highest *p*H values, potentially increasing their susceptibility to microbial growth. This result is likely due to the alkaline nature of spirulina, containing proteins with amphoteric properties and mineral compounds with buffering capacity [41]. When spirulina was combined with cricket flour and/or soy protein, lower *p*H values comparable to those of the control sample were observed.

***Table 3**. Physicochemical parameters (pH, color values, water activity) of baked pork meatballs containing soy protein, spirulina, and cricket powder*

Parameter	**Samples**						
	S	**Sp**	**CP**	**SSp**	**SCP**	**SpCP**	**SSpCP**
*p*H	6.56 ± 0.07^{ab}	6.72 ± 0.04^{c}	6.53 ± 0.03^{a}	6.65 ± 0.08^{c}	6.62 ± 0.03^{ab}	6.56 ± 0.08^{ab}	6.54 ± 0.02^{a}
a_W	0.887 ± 0.006^{c}	0.849 ± 0.002^{b}	0.850 ± 0.008^{a}	0.833 ± 0.007^{b}	0.831 ± 0.007^{a}	0.837 ± 0.009^{a}	0.835 ± 0.004^{a}
L*	44.49 ± 3.13^{d}	29.03 ± 3.51^{a}	39.2 ± 1.94^{cd}	31.27 ± 3.98^{ab}	36.78 ± 4.09^{bc}	26.72 ± 1.23^{a}	30.47 ± 3.06^{a}
a *	9.56 ± 1.05^{cd}	2.11 ± 0.84^{a}	8.54 ± 0.64^{cd}	7.1 ± 5.11^{bc}	11.41 ± 3.18^{d}	3.51 ± 0.79^{ab}	8.55 ± 1.56^{cd}
*	18.86 ± 1.00^{b}	9.32 ± 1.33^{a}	16.67 ± 0.93^{b}	10.31 ± 0.59^{a}	15.47 ± 4.08^{b}	10.37 ± 0.88^{a}	15.06 ± 3.47^{b}
C	21.16 ± 0.88^{c}	13.62 ± 6.20^{ab}	18.29 ± 1.04^{bc}	13.03 ± 2.49^{a}	19.65 ± 1.23^{c}	10.92 ± 1.09^{a}	20.12 ± 3.08^{c}
h	63.1 ± 3.13^{ab}	73.00 ± 8.78^{b}	62.15 ± 1.42^{ab}	67.89 ± 9.99^{b}	56.3 ± 9.46^{a}	71.40 ± 2.59^{b}	66.77 ± 2.31^{ab}

Note: Values are expressed as mean ± standard deviation (n = 3). Different superscript letters within the same column indicate significant differences ($P < 0.05$). S – soy protein (control); Sp – spirulina; CP – cricket powder; SSp – soy + spirulina; SpCP – spirulina + cricket powder; SSpCP – soy + spirulina + cricket powder.

Regarding water activity, the samples containing spirulina and cricket flour (Sp, CP, and SpCP) showed lower values (0.831 - 0.85) compared to the control sample containing soy protein (S, $a_W = 0.887$). The reduction in a_W is likely due to the higher content of proteins and dietary fibers, binding part of the free water in the product. These lower water activity values suggest improved microbiological stability and a potentially longer shelf life for samples containing alternative protein sources.

Color is a main quality indicator of meat products and strongly influences consumer perception [42, 43]. Table 3 presents the values of the parameters L* (lightness), a* (red component), b* (yellow component), as well as the calculated chroma (C) and hue angle (h).

The lightness (L*) values ranged from 26.72 in sample SpCP to 44.49 in the control sample S, with all experimental samples differing significantly ($P < 0.05$). The lower L* values in samples containing spirulina are due to its dark green pigment, while samples with cricket flour exhibit a naturally brownish tint, consistent with the results reported by [44] and [1].

For the a* parameter, the lowest value was observed in the Sp sample, and the highest in SCP (50 % soy and 50 % cricket flour), while CP did not differ statistically from the control ($P > 0.05$). Regarding the yellow component (b*), the lowest values were again recorded for Sp, and slightly higher ones for CP, which may be attributed to the greenish hue of cricket flour [45].

The lowest chroma (C) value was recorded for SpCP (10.92 ± 1.09), while the highest was found in the control sample (21.16 ± 0.88). The decrease in h values indicates a shift of color toward reddish tones, with the lowest h observed in SCP, whereas higher values in spirulina-containing samples correspond to yellowish-green hues.

Oxidation analysis

Oxidative stability is a key parameter determining the quality and shelf life of meat products [46 – 48]. The content of thiobarbituric acid reactive substances (TBARS), expressed as mg MDA per kg sample, serves as an indicator of the extent of lipid oxidation and the formation of secondary oxidation products [49]. As shown in Table 4, lower TBARS values were observed in the baked samples containing cricket flour (CP, SCP, SpCP, and SSpCP) despite their higher fat content (Table 2).

Table 4. *Oxidative stability of baked pork meatballs formulated with soy protein, spirulina, and cricket powder, expressed as TBARS values and DPPH radical scavenging activity*

Parameter	**Samples**						
	S	**Sp**	**CP**	**SSp**	**SCP**	**SpCP**	**SSpCP**
TBARS, [mg MDA·kg^{-1}]	0.76± 0.08^{c}	0.41± 0.05^{a}	0.39± 0.03^{a}	0.57± 0.04^{b}	0.31± 0.08^{a}	0.34± 0.07^{a}	0.31± 0.08^{a}
DPPH [µmol TE/100 g]	40.0± 2.1^{a}	54.0± 2.2^{b}	144.0± 2.9^{e}	41.0± 2.1^{a}	87.0± 1.9^{d}	70.0± 2.3^{c}	72.0± 2.4c

Note: Values are expressed as mean ± standard deviation (n = 3). Different superscript letters within the same column indicate significant differences ($P < 0.05$). S – soy protein (control); Sp – spirulina; CP – cricket powder; SSp – soy + spirulina; SpCP – spirulina + cricket powder; SSpCP – soy + spirulina + cricket powder.

The observed stabilizing effect of cricket flour on the lipid phase and the improved oxidative resistance of thermally processed products is likely due to the presence of bioactive compounds with antioxidant activity, such as peptides, phenolic components, and chitin-derived substances, which can neutralize free radicals and chelate metal ions [50, 51].

The high antioxidant activity of the samples containing cricket flour was further confirmed by the DPPH analysis results (Table 4), with the highest value recorded for sample CP (144 µmol TE/100 g), followed by SCP and the combined samples SpCP and SSpCP. The addition of spirulina also exerted a beneficial effect on oxidative stability, as the Sp and SpCP samples showed lower TBARS values and higher antioxidant potential compared to the soy-containing control sample (S). Spirulina has been widely reported to exhibit strong antioxidant activity, mainly attributed to its high content of phycocyanin, carotenoids, and phenolic compounds, which contribute to its radical scavenging capacity [52]. Its incorporation in meat systems by feeding has also been associated with improved oxidative stability and reduced lipid oxidation [53].

Analysis of emulsion stability, textural profile, and baking yield

The results for emulsion stability, textural parameters, and baking yield of the control and experimental samples are presented in Table 5. All samples exhibited high emulsion stability (96.18 - 99.67 %), indicating the formation of an effective protein matrix and a good balance between the aqueous and lipid phases. The lowest values were recorded for the samples with the combined inclusion of spirulina and cricket flour (SpCP, SSpCP), likely due to their higher protein content and more pronounced protein denaturation during heating. This may limit their ability to form a stable interfacial film around fat globules and partially reduce their water-holding capacity. Nevertheless, all values remained within the typical range for well-stabilized meat systems [54, 55].

Table 5. *Emulsion stability, textural parameters, and baking yield of baked pork meatballs containing soy protein, spirulina, and cricket powder*

Parameter	**Samples**						
	S	**Sp**	**CP**	**SSp**	**SCP**	**SpCP**	**SSpCP**
Hardness [N]	54.12± 17.11^{ab}	44.07± 7.53^{a}	53.47± 4.27^{ab}	52.90± 5.16^{ab}	59.17± 9.18^{ab}	83.51± 12.25^{c}	73.19± 22.78^{bc}
Springiness	0.99± 0.00^{a}	0.99± 0.00^{a}	0.99± 0.00^{a}	0.99± 0.00^{a}	0.99± 0.00^{a}	1.00± 0.00^{a}	0.99± 0.00^{a}
Cohesiveness	0.07± 0.00^{a}	0.06± 0.00^{a}	0.07± 0.00^{a}	0.06± 0.00^{a}	0.07± 0.00^{a}	0.06± 0.00^{a}	0.07± 0.00^{a}
Gumminess [N]	3.64± 1.18^{ab}	2.65± 0.43^{a}	3.52± 0.32^{ab}	3.19± 0.16^{a}	3.89± 0.39^{abc}	5.42± 1.17^{c}	4.77± 1.49^{bc}
Chewiness [N]	7.76± 2.51^{ab}	5.65± 0.91^{a}	7.49± 0.68^{ab}	6.78± 0.34^{a}	8.29± 0.83^{abc}	11.58± 2.56^{c}	10.17± 3.19^{bc}
Adhesiveness [N mm]	0±0^{a}	0±0^{a}	0±0^{a}	0±0^{a}	0±0^{a}	0±0^{a}	0±0^{a}
ES [%]	99.67± 0.30^{b}	99.64± 0.20^{b}	99.12± 0.90^{b}	99.58± 0.40^{b}	99.04± 0.30^{b}	96.66± 0.20^{a}	96.18± 0.80^{a}
Baking yield [%]	64.79± 2.16^{d}	68.53± 2.70^{e}	60.03± 3.09^{c}	58.75± 2.78^{c}	58.00± 3.00^{c}	55.49± 3.81^{b}	51.61± 4.19^{a}

Note: Values are expressed as mean ± standard deviation (n = 3). Different superscript letters within the same column indicate significant differences ($P < 0.05$). S – soy protein (control); Sp – spirulina; CP – cricket powder; SSp – soy + spirulina; SpCP – spirulina + cricket powder; SSpCP – soy + spirulina + cricket powder.

The texture profile results correspond well with the observations on chemical composition and emulsion stability. The highest values of hardness, gumminess, and chewiness were recorded for samples SpCP and SSpCP, which correlate with their higher protein content and lower moisture levels. Thermal processing in these variants likely led to stronger protein denaturation and aggregation, resulting in the formation of a denser, more cohesive protein matrix. Conversely, the control sample containing soy protein (S) and the sample with spirulina only (Sp) showed lower hardness and a softer texture, consistent with its higher moisture content and the better hydration capacity of the incorporated proteins.

Baking yield also shows statistically significant differences among samples ($P < 0.05$). The highest yield was recorded for the spirulina sample (Sp - 68.53 %), while the lowest values were observed in the variants with a combined inclusion of spirulina and cricket flour (SpCP - 55.49 %; SSpCP - 51.61 %). This trend was consistent with the observed higher hardness of these samples and lower emulsion stability, resulting from the interrelationship among the degree of protein denaturation, water-holding capacity, and thermal losses. The reduced yield in samples containing cricket flour was likely due to the altered ability of the denatured proteins to retain water and fat in the matrix during heating. Conversely, the higher yield in the Sp sample is likely due to the hydration properties of the proteins and polysaccharides present in spirulina, which may contribute to better water retention in the cooked meat samples. Similar effects of spirulina and cricket flour have been observed in other meat systems enriched with these alternative protein sources [44].

Sensory analysis

The results of the sensory evaluation of the baked meat semi-finished products are presented in Table 6.

Table 6. *Sensory characteristics of baked pork meatballs formulated with soy protein, spirulina, and cricket powder*

Parameter	**Samples**						
	S	**Sp**	**CP**	**SSp**	**SCP**	**SpCP**	**SSpCP**
Appearance	8.2±0.8^{d}	5.6±2.3^{a}	7.3±1.5^{abcd}	8.8±2.5^{ab}	7.6±1.1^{cd}	6.3±2.3^{abc}	7.3±1.4^{bcd}
Color	7.9±1.2^{c}	5.4±2.3^{a}	7.6±1.8^{bc}	6.0±2.5^{ab}	7.2±1.1^{abc}	6±2.4^{ab}	6.8±1.9^{abc}
Consistency	7.4±1.9^{a}	6.7±2.3^{a}	7.1±1.6^{a}	6.4±2.2^{a}	7±1.1^{a}	6.3±1.5^{a}	7.1±1.9^{a}
Taste	7.3±2.1^{a}	6.6±1.5^{a}	7.7±1.2^{a}	7.1±1.7^{a}	7.3±1.8^{a}	6.7±1.4^{a}	7.2±1.9^{a}
Aroma	7.5±1.9^{a}	7.3±1.2^{a}	8±0.8^{a}	7.4±1.9^{a}	7.7±1.4^{a}	6.6±2.2^{a}	7.2±1.9^{a}
Aftertaste	7.7±1.2^{b}	6.2±1.7$^{a\ b}$	7.6±1.2^{ab}	6.9±1.8^{ab}	7.1±1.7^{ab}	6.1±2.2^{a}	7.6±1.4^{ab}
Saltiness	7.8±1.5^{a}	6.6±2.0^{a}	7.8±0.6^{a}	6.7±2.0^{a}	6.7±2.1^{a}	6.8±1.5^{a}	6.6±1.8^{a}
Overall sensory acceptance	7.7± 0.87^{b}	6.2± 1.54^{a}	7.2± 1.56^{ab}	6.2± 1.79^{a}	7.1± 1.17^{ab}	6.4± 1.27^{ab}	7.0± 1.79^{ab}

Note: Values are expressed as mean ± standard deviation (n = 3). Different superscript letters within the same column indicate significant differences ($P < 0.05$). S – soy protein (control); Sp – spirulina; CP – cricket powder; SSp – soy + spirulina; SpCP – spirulina + cricket powder; SSpCP – soy + spirulina + cricket powder.

The main attributes assessed were appearance, color, texture, taste, aroma, aftertaste and saltiness. The control sample with soy protein (S) received the highest mean scores for nearly all attributes, particularly for appearance and color (8.2 and 7.9 points, respectively). This is expected, as soy protein has a neutral flavor and well-established functional properties in meat systems.

Samples containing cricket flour (CP, SCP, and SSpCP) maintained good sensory characteristics comparable to the control, with sample CP showing the highest scores for aroma (8.0) and aftertaste (7.6), without statistically significant differences from the control ($P > 0.05$). This suggests that inclusion of cricket flour does not adversely affect the flavor perception of baked pork meatballs.

Samples containing only spirulina (Sp) received lower scores for appearance and color (5.6 and 5.4, respectively), due to its dark green pigment and characteristic plant-like aroma. The combined samples with spirulina and cricket flour (SpCP, SSpCP) showed slight improvement compared to Sp, but still exhibited lower overall sensory scores compared to the control. No statistically significant differences were observed among the samples regarding saltiness ($P > 0.05$).

In summary, replacing soy protein with cricket flour preserves the desirable sensory characteristics of baked meatballs. While the use of spirulina in moderate amounts affects color and appearance but does not significantly impair the taste or aroma quality of the final product.

CONCLUSIONS

The present study provided an elaborate assessment of the technological potential and nutritional advantages of spirulina and cricket flour in thermally processed meat products. The results demonstrated that replacing soy protein with cricket flour and spirulina significantly affected the compositional, oxidative, technological, and sensory properties of baked pork meatballs. Cricket flour contributed mainly to increased protein and antioxidant capacity, while spirulina contributed to higher dietary fiber content and improved oxidative stability but less favorable color characteristics.

Their combined use increased protein content, with the highest value observed in sample SpCP (20.24 %), enhanced antioxidant activity (up to 144 µmol TE/100 g), and reduced lipid oxidation (TBARS values as low as 0.31 mg $MDA\cdot kg^{-1}$). The combination of these ingredients resulted in firmer textures, as reflected by higher hardness, gumminess, and chewiness values. Although all formulations exhibited relatively high emulsion stability, the combined variants showed lower baking yield and less favorable appearance compared to the control.

These findings highlight the potential for integrating sustainable protein sources into conventional meat products and demonstrate their complementary effects, supporting their application in the development of functional and environmentally friendly meat products. However, further formulation optimization is required to achieve a better balance between oxidative stability, texture, yield, and sensory acceptability.

ACKNOWLEDGMENT

The study was carried out under project TN 15 of the Agricultural Academy, Task 1, entitled "Investigation of the possibilities for using different protein sources in meat semi-finished products and their influence on quality characteristics and technological properties."

REFERENCES

1. Žugčić, T., Abdelkebir, R., Barba, F.J., Rezek-Jambrak, A., Gálvez, F., Zamuz, S., Granato, D., Lorenzo, J.M.: Effects of pulses and microalgal proteins on quality traits of beef patties, *Journal of Food Science and Technology*, **2018**, **55** (11), 4544-4553;
2. Jiménez Colmenero, F., Delgado Pando, G.: Fibre-enriched meat products in: *Fibre-Rich and Wholegrain Foods: Improving Quality* (Editors: Delcour, J. A., Poutanen, K.), Woodhead Publishing Limited, UK, **2013**, 329-347;
3. Birghila, S., Radu, M.D., Dumbrava, A.: Hydrolyzed collagen from meat by-product sources: extraction and characterization, *Scientific Study & Research. Chemistry & Chemical Engineering, Biotechnology, Food Industry*, **2025**, **26** (4), 455-469;
4. Hooper, L., Martin, N., Jimoh, O. F, Kirk, C., Foster, E., Abdelhamid, A. S.: Reduction in saturated fat intake for cardiovascular disease, *Cochrane Database of Systematic Reviews*, **2020**, **8**, CD011737;
5. Asgar, M.A., Fazilah, A., Huda, N., Bhat, R., Karim, A.A.: Nonmeat protein alternatives as meat extenders and meat analogs, *Comprehensive Reviews in Food Science and Food Safety*, **2010**, **9** (5), 513-529;

6. Rinaldoni, A.N., Palatnik, D.R., Zaritzky, N., Campderro´s, M.E.: Soft cheese-like product development enriched with soy protein concentrates, *LWT - Food Science and Technology*, **2014**, **55** (1),139-147;
7. Spychaj, A., Pospiech, E., Iwańska, E., Montowska, M.: Detection of allergenic additives in processed meat products, *Journal of the Science of Food and Agriculture*, **2018**, **98** (13), 4807-4815;
8. Firdaus, F., Panjaitan, T.S., Makmur, M., Atmoko, B.A., Adinata, Y., Krishna, N.H., Widiyawati, R.: Spirulina supplementation effects on small ruminants performance and product attributes: A meta-analysis, *Animal Bioscience*, **2025**, **38** (8), 1680-1693;
9. Drăghici, O., Marcu, G.D.: The physicochemical properties of a commercial cricket (Acheta domesticus) protein powder as a basis for its use in food products, *Scientific Study & Research: Chemistry & Chemical Engineering, Biotechnology, Food Industry*, **2023**, **24** (4), 279-289;
10. Gumbo, J., Nesamvuni, C.A.: Review: Spirulina a source of bioactive compounds and nutrition, *Journal of Chemical and Pharmaceutical Sciences*, **2017**, **10** (3), 1317;
11. Shimamatsu, H.: Mass production of Spirulina, an edible microalga, *Hydrobiologia*, **2004**, **512** (1), 39-44;
12. Kim, T.K., Yong, H.I., Kim, Y.B., Kim, H.W., Choi, Y.S.: Edible insects as a protein source: a review of public perception, processing technology, and research trends, *Food Science of Animal Resources*, **2019**, **39** (4), 521-540;
13. Villaseñor, V.M., Enriquez-Vara, J.N., Urías-Silva, J.E., Mojica, L.: Edible Insects: Techno-functional Properties Food and Feed Applications and Biological Potential, *Food Reviews International*, **2022**, **38**, 866-892;
14. Moura, M.A.F.E., Martins, B.d.A., Oliveira, G.P.D., Takahashi, J.A.: Alternative protein sources of plant, algal, fungal and insect origins for dietary diversification in search of nutrition and health, *Critical Reviews in Food Science and Nutrition*, **2023**, **63** (31), 10691-10708;
15. Soleha, D.H., Dekker, M., Mishyna, M.: Understanding the Influence of Sensory Characteristics on Emotional Responses and Acceptance of Insect-Based Spreads, *Journal of Texture Studies*, **2025**, **56** (5), e70045;
16. Kim, T.K., Yong, H.I., Cha, J.Y., Hwang, K.E., Choi, Y.S., Jung, S.: Quality characteristics of meat products with edible insect protein, *Korean Journal for Food Science of Animal Resources*, **2016**, **36** (1), 48-54;
17. Cavalheiro, C.P., Ruiz-Capillas, C., Herrero, A.M., Pintado, T., Cruz, T. da M.P., Alves da Silva, M.C.: Cricket (Acheta domesticus) flour as meat replacer in frankfurters: Nutritional, technological, structural, and sensory characteristics, *Innovative Food Science & Emerging Technologies*, **2023**, **83**, 103245;
18. Vlahova-Vangelova, D.B., Balev, D.K., Kolev, N.D., Gradinarska, D.N., Dragoev, S.G.: Cricket powder (*Acheta domestica*) as food additive for processing of dry-fermented poultry bars, *Scientific Study & Research. Chemistry & Chemical Engineering, Biotechnology, Food Industry*, **2021**, **22** (4), 453-461;
19. Kassymov, S., Rebezov, M., Ikonnikova, A., Fedin, I., Rodionov, I., Rukhadze, S., Bokuchava, O.: Using of pumpkin and carrot powder in production of meat cutlets: effect on chemical and sensory properties, *International Journal of Psychosocial Rehabilitation*, **2020**, **24** (4), 1663-70;
20. International Organization for Standardization: ISO 5983-1:2006 Animal Feeding Stuffs - Determination of Nitrogen Content and Calculation of Crude Protein Content – Part 1: Kjeldahl Method, ISO, Geneva, **2006**;
21. International Organization for Standardization: ISO 1443:1973 Meat and Meat Products - Determination of Total Fat Content, ISO, Geneva, **1973**;
22. International Organization for Standardization: ISO 936:1998 Meat and Meat Products - Determination of Total Ash, ISO, Geneva, **1998**;
23. AOAC International: Official Method 985.29 Total Dietary Fiber in Foods – Enzymatic - Gravimetric Method, In *Official Methods of Analysis of AOAC International*, AOAC International, Gaithersburg, MD, **1985**;
24. Food and Agriculture Organization of the United Nations: Food Energy – Methods of Analysis and Conversion Factors, FAO, Rome, **2019**;
25. International Organization for Standardization: ISO 1841-1:1996 Meat and Meat Products - Determination of Chloride Content – Part 1: Volhard Method (Modified Mohr Method), ISO, Geneva, **1996**;

26. International Organization for Standardization: ISO 18787:2017 Food and Feed Products - Determination of Water Activity, ISO, Geneva, **2017**;
27. Cabral, N.O., Oliveira, R.F., Henry, F.C., de Oliveira, D.B., do Santos Junior, A.C., Maia Junior, J.A., Martines, M.L.L.: Effect of the fruit aqueous extract of balloon pepper (Capsicum baccatum var. Pendulum) on lipid oxidation, microbiological quality and consumer acceptance of fresh pork sausage and smoked, *Food Science and Technology*, **2021**, **42**, 1-8;
28. Brand-Williams, W.: Use of a free radical method to evaluate antioxidant activity, *Journal of Food Science and Technology*, **1999**, **28**, 1231-1237;
29. Petrova, K., Ivanova, P., Mihalev, K., Georgiev, D.: Antioxidant capacity, polyphenol and anthocyanin content in blackberries, *Journal of Mountain Agriculture on the Balkans*, **2016**, **19** (2), 221-232;
30. Zorba, Ö., Kurt, Ş.: Optimization of emulsion characteristics of beef, chicken and turkey meat mixtures in model system using mixture design, *Meat Science*, **2006**, **73** (4), 611-618;
31. Murphy, E.W., Criner, P.E., Grey, B.C.: Comparision of methods for calculating retentions of nutrients in cooked foods, *Journal of Agricultural and Food Chemistry*, **1975**, **23**, 1153-1157;
32. Bourne, M.C.: Texture profile analysis, *Food Technology*, **1978**, **32**, 62-66;
33. Bourne, M.: Food Texture and Viscosity – Concept and Measurement, 2nd edition, Academic Press, New York, **2002**;
34. Kim, E.J., Corrigan, V.K., Hedderley, D.I., Motoi, L., Wilson, A.J., Morgenstern, M.P.: Predicting the sensory texture of cereal snack bars using instrumental measurements, *Journal of Texture Studies*, **2009**, **40** (4), 457-481;
35. Ruiz-Capillas, C., Herrero, A.M., Pintado, T., Delgado-Pando, G.: Sensory analysis and consumer research in new meat products development, *Foods*, **2021**, **10** (2), 429;
36. Kolev, N., Vlahova-Vangelova, D., Balev, D., Dragoev, S., Dimov, K., Petkov, E., Popova, T.: Effect of the addition of soybean protein and insect flours on the quality of cooked sausages, *Foods*, **2024**, **13** (14), 2194;
37. Podgórska-Kryszczuk, I.: Spirulina-An invaluable source of macro-and micronutrients with broad biological activity and application potential, *Molecules*, **2024**, **29** (22), 5387;
38. Citi, V., Torre, S., Flori, L., Usai, L., Aktay, N., Dunford, N.T., Lutzu, G.A., Nieri, P.: Nutraceutical features of the phycobiliprotein c-phycocyanin: Evidence from Arthrospira platensis (Spirulina), *Nutrients*, **2024**, **16** (11), 1752;
39. Janda-Milczarek, K., Szymczykowska, K., Jakubczyk, K., Kupnicka, P., Skonieczna-Żydecka, K., Pilarczyk, B., Tomza-Marciniak, A., Ligenza, A., Stachowska, E., Dalewski, B.: Spirulina supplements as a source of mineral nutrients in the daily diet, *Applied Sciences*, **2023**, **13**, 1011;
40. Momchilova, M.M., Gradinarska-Ivanova, D.N., Valkova-Yorgova, K.I., Yordanov, D.G.: Comparative analysis of the effect of cricket powder and spirulina in model meat systems as substitutes for soy in raw pork products, *Bulgarian Chemical Communications*, **2025**, **57** (2), 94-101;
41. Marjanović, B., Benković, M., Jurina, T., Sokač Cvetnić, T., Valinger, D., Gajdoš Kljusurić, J., Jurinjak Tušek, A.: Bioactive compounds from *spirulina* spp.-nutritional value, extraction, and application in food industry, *Separations*, **2024**, **11** (9), 257;
42. Hamm, U.: Verbraucherakzeptanz von Öko-Fleischwaren ohne Nitritpökelsalz, *Fleischwirtschaft*, **2007**, **87** (11), 126-130;
43. Mancini, R.A., Hunt, M.: Current research in meat color, *Meat Science*, **2005**, **71** (1), 100-121;
44. Ho, I., Peterson, A., Madden, J., Huang, E., Amin, S., Lammert, A.: Will it cricket? Product development and evaluation of cricket (Acheta domesticus) powder replacement in sausage, pasta, and brownies, *Foods*, **2022**, **11** (19), 3128;
45. Smarzyński, K., Sarbak, P., Musiał, S., Jeżowski, P., Piątek, M., Kowalczewski, P.Ł.: Nutritional analysis and evaluation of the consumer acceptance of pork pâté enriched with cricket powder-preliminary study, *Open Agriculture*, **2019**, **4** (1), 159-163;
46. Chaijan, M., Panpipat, W.: Mechanism of oxidation in foods of animal origin in: *Natural antioxidants* (Editors: Banerjee, R., Verma, A. K., Siddiqui, M. W.), Apple Academic Press, **2017**, 21-58;
47. Shah, M.A., Bosco, S.J.D., Mir, S.A.: Plant extracts as natural antioxidants in meat and meat products, *Meat Science*, **2014**, **98** (1), 21-33;

48. Devatkal, S.K., Thorat, P., Manjunatha, M.: Effect of vacuum packaging and pomegranate peel extract on quality aspects of ground goat meat and nuggets, *Journal of Food Science and Technology*, **2014**, **51**, 2685-2691;
49. Phetsang, H., Panpipat, W., Undeland, I., Panya, A., Phonsatta, N., Chaijan, M.: Comparative quality and volatilomic characterisation of unwashed mince, surimi, and pH-shift-processed protein isolates from farm-raised hybrid catfish (Clarias macrocephalus× Clarias gariepinus), *Food Chemistry*, **2021**, **364**, 130365;
50. Fashakin, O.O., Tangjaidee, P., Unban, K., Klangpetch, W., Khumsap, T., Sringarm, K., Rawdkuen, S., Phongthai, S.: Isolation and identification of antioxidant peptides derived from cricket (*Gryllus bimaculatus*) protein fractions, *Insects*, **2023**, **14** (8), 674;
51. Quinteros, M.F., Martínez, J., Barrionuevo, A., Rojas, M., Carrillo, W.: Functional, Antioxidant, and Anti-Inflammatory Properties of Cricket Protein Concentrate (Gryllus assimilis), *Biology*, **2022**, **11** (5), 776;
52. Wu, Q., Liu, L., Miron, A., Klímová, B., Wan, D., Kuča, K.: The antioxidant, immunomodulatory, and anti-inflammatory activities of Spirulina: an overview, *Archives of toxicology*, **2016**, **90** (8), 1817-1840;
53. Spínola, M.P., Costa, M.M., Prates, J.A.: Effect of cumulative Spirulina intake on broiler meat quality, nutritional and health-related attributes, *Foods*, **2024**, **13** (5), 799;
54. Santhi, D., Kalaikannan, A., Sureshkumar, S.: Factors influencing meat emulsion properties and product texture: A review, *Critical Reviews in Food Science and Nutrition*, **2015**, **55** (9), 1242-1253;
55. Tornberg, E.: Effects of heat on meat proteins - Implications on structure and quality of meat products, *Meat Science*, **2005**, **70** (3), 493-508.