

## Article

# Sustainable Protein Fortification: Impact of Hemp and Cricket Powder on Extruded Snack Quality

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**Abstract:** This research paper evaluates the functional and nutritional properties of extruded corn snacks fortified with plant-based hemp protein (HP) and insect-derived cricket powder (CP). With a focus on sustainable protein sources due to growing environmental concerns and the need for alternative protein sources, this study aims to enhance the nutritional profile of corn snacks. The incorporation of unconventional proteins into snacks is explored to meet consumer demands for sustainable and nutritious options. Results show that HP-enriched snacks have higher mineral content, such as calcium and magnesium, lower sodium content, and improved water interaction profiles. On the other hand, CP-fortified snacks exhibit higher protein content, essential amino acids, and moisture retention capabilities. Texture analysis reveals differences in hardness, cohesiveness, and springiness between HP and CP-enriched products. Moreover, color analysis indicates that HP and CP additives influence the color and appearance of the snacks, with CP enrichments leading to darker snacks. Sorption isotherm studies demonstrate varying hygroscopicity levels between HP- and CP-enriched samples, impacting their storage stability. Surface structure assessments show differences in the specific sorption surface area, suggesting unique properties attributed to each protein source. In conclusion, both hemp protein and cricket powder offer various advantages for snack fortification, providing opportunities to enhance nutritional profiles while addressing sustainability concerns.

**Keywords:** fortified corn snacks; plant-based hemp protein; insect-derived cricket powder; snack fortification



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## 1. Introduction

The global food industry is undergoing a transformation driven by shifting consumer preferences, sustainability concerns, and the growing demand for alternative protein sources. As the world's population continues to rise, traditional animal-derived proteins are increasingly scrutinized due to their environmental impact and resource-intensive production [1]. Consequently, researchers and food technologists are actively seeking alternative protein sources that are sustainable, nutritious, and widely acceptable [2].

Among these alternatives, plant-based proteins and insect-derived proteins have gained significant interest due to their functional and nutritional benefits.

Fortifying corn snacks with different micro- and macronutrients presents a valuable opportunity to enhance their nutritional profile [3–5]. Protein-rich extruded snacks could serve as a convenient means of delivering essential amino acids to diverse consumer groups, who seek sustainable protein options. Additionally, understanding the effects of different protein sources on the textural, sensory, and physicochemical properties of extruded snacks is crucial for optimizing product quality and consumer acceptance. The extrusion process is widely used in the production of corn-based snacks, offering an effective method for incorporating novel protein ingredients. Prior research has explored the incorporation of various protein-rich ingredients, such as soy [6,7], flaxseed meal [8,9], buckwheat [10,11], and insect powders like cricket powder [12], into extruded snack formulations. However, a direct comparison of plant and insect proteins in terms of their impact on the functional and nutritional properties of extruded corn snacks is still lacking.

Hemp (*Cannabis sativa*) protein (HP) is gaining attention as a high-quality plant-based protein source due to its excellent amino acid profile, digestibility, and functional properties [13,14]. HP is widely recognized for its complete amino acid profile. Multiple studies confirm that hemp protein contains all nine EAAs. For example, hemp seeds have been described as a “complete protein” due to their amino acid composition [15,16]. The amino acid profile of HP is not only complete but also compares favorably to the “ideal protein” recommended by the World Health Organization (WHO) [17,18]. Its mild flavor and functional attributes make it a promising ingredient for fortifying extruded snacks without significantly altering their sensory characteristics.

Insect-derived protein, including cricket (*Acheta domesticus*) powder (CP), offers a sustainable and nutrient-dense alternative to traditional (animal-based) protein sources. It boasts a high protein content, typically exceeding 60%, along with essential vitamins and minerals such as iron, zinc, and B vitamins [19]. Moreover, insect farming requires significantly less land, water, and feed compared to conventional livestock, making it an environmentally friendly protein source [20–22]. The incorporation of insect protein into extruded snacks can enhance their nutritional value while contributing to global food security and sustainability efforts. Despite the fact that current prices for edible insects remain relatively high [23,24], a combination of appropriate regulatory frameworks, support programs, innovative technologies, and educational initiatives, along with integration into the waste management industry through circular economy principles, economies of scale, and the development of breeding clusters, holds significant potential to enhance the profitability of cricket farming. Additionally, the development of alternative energy sources for farming, genetic optimization of crickets for improved breeding efficiency, digitalization, and the use of artificial intelligence in farm management, as well as shifts in marketing strategies and the creation of international quality standards for insect protein, may play a pivotal role in increasing the economic viability of cricket farming across different regions of the world. Moreover, several studies have demonstrated that insect farming typically results in lower CO<sub>2</sub> emissions, reduced water consumption, and decreased energy usage compared to conventional livestock farming. For instance, it has been reported that insects emit up to 80% less greenhouse gases than cattle per unit of protein produced [25]. Furthermore, insect farming requires significantly less water, with figures indicating that the water consumption for producing 1 kg of insect protein is substantially lower than that of beef or pork production [26]. In terms of energy use, the efficiency of insect farming is also notable as insects can be reared on organic waste, thus reducing the need for external inputs. These data emphasize the potential of insect-based proteins as a more sustainable alternative to traditional protein sources.

Considering the above, the aim of this research was to evaluate the functional and nutritional properties of extruded corn snacks fortified with plant-based and insect-derived proteins, providing insights into their potential as sustainable protein sources in snack formulations. With rising concerns over malnutrition and the environmental impact of traditional protein sources, this research highlights the potential of both plant-based and insect-derived proteins to enhance the nutritional profile of extruded snacks.

## 2. Materials and Methods

### 2.1. Production of Extruded Corn Snacks

The extrudates were made using a starch-based raw material of Polish origin—corn grits from the Piatnica brand (Piatnica, Poland), hemp (*C. sativa*) protein (HP) from the Energy Feelings (Tarragona, Spain), and house cricket (*A. domesticus*) powder (CP) from the JR Unique Foods (Thailand). Disodium diphosphates and sodium carbonates contained in Dr. Oetker baking powder were used as leavening agents. The extruded corn snacks were produced using a single-screw extruder, model S 45A-12-10U (Metalchem, Gliwice, Poland). The extrusion process was conducted at a screw speed of 125 rpm, with a temperature profile of 105 °C, 130 °C, and 110 °C for zone I, zone II, and the die head, respectively. The die diameter was set at 4.5 mm. As a result of the extrusion process, extrudates with varying levels of protein fortification (2%, 4%, and 7%), both hemp protein (HP) and cricket powder (CP), were produced, along with a control extrudate (reference product, R) without any protein addition (Table 1). The applied percentage levels of the additives were selected based on preliminary studies to ensure that the production of extrudates was of appropriate quality and to enable the extrusion process to proceed without disruptions. The extrudates were cooled, packed in airtight polyethylene bags, and stored in a cool and dry place until further analysis.

**Table 1.** Corn extrudates detailed compositions.

Sample Code	Percentage of the Component (%)			
	Corn Grits	Hemp Protein (HP)	Cricket Protein (CP)	Baking Powder
R	98	0	0	2
HP2	96	2	0	2
HP4	94	4	0	2
HP7	91	7	0	2
CP2	96	0	2	2
CP4	94	0	4	2
CP7	91	0	7	2

### 2.2. Evaluation of Nutritional Value

Tested samples were analyzed for protein content using the Kjeldahl titration method according to ISO 1871 [27], based on the determined nitrogen content. Additionally, the gravimetric method (PB/CH/16) was applied to determine the fat content after hydrolysis. Ash content determination was performed using a gravimetric method by first charring the sample on an electric plate and subsequently incinerating the tested extrudates in a muffle furnace at 600 °C. The samples were cooled and weighed, with the determination repeated until a constant mass was obtained. Based on the obtained results, as well as moisture content analysis, the energy value (EU Regulation 1169/2011) and carbohydrate content were calculated.

### 2.3. Amino Acids Composition

The amino acid composition was determined by ion-exchange chromatography after 23 h hydrolysis with 6N HCl at 110 °C. The hydrolyzed amino acids were analyzed using an AAA-400 analyzer (INGOS, Prague, Czech Republic) with a photometric detector operating at two wavelengths: 440 nm and 570 nm. A 350 × 3.7 mm column filled with Ostion LG ANB ion exchanger (INGOS, Prague, Czech Republic) was used. The column temperature was maintained at 60–74 °C, while the detector temperature was set at 121 °C. Prepared samples were analyzed using the ninhydrin method.

### 2.4. Minerals Profiles

The concentrations of mineral compounds (Ca, Cu, Fe, K, Mg, Mn, Na, and Zn) in the analyzed extrudates were determined using flame atomic absorption spectroscopy (FAAS) (SpectrAA-800, Varian, Palo Alto, CA, USA), following microwave-assisted digestion with nitric acid.

### 2.5. Instrumental Color Measurement

The spectrophotometric color assessment was conducted for the minced product using a CR 400 colorimeter (Konica-Minolta, Japan), with samples placed in a glass cuvette. The measurements were carried out in the CIE L\* a\* b\* system, which allows for a mathematical representation of color using three descriptive variables: L\*, a\*, and b\*. The first parameter, L\*, represents lightness, ranging from 0 for black to 100 for white. The parameters a\* and b\* range from −120 to 120, describing the color spectrum from green to red (a\*) and from blue to yellow (b\*), respectively. The measurements were conducted in 10 repetitions. The obtained color values of the produced samples were used to calculate the color difference parameter ( $\Delta E$ ) [9].

### 2.6. Evaluation of the Water Absorption Index (WAI)

The determination of the Water Absorption Index (WAI) was conducted based on the methodologies of Anderson et al. [28]. For the analysis, a 2 g sample was weighed, and 20 mL of distilled water was used. A mixture was prepared from extrudate ground into a powder with a particle size of less than 0.3 mm using a laboratory mill and distilled water, which was then thoroughly mixed. The prepared solution was centrifuged using a Jouan B 4i laboratory centrifuge (Thermo Fisher Scientific Inc., Waltham, MA, USA) with a speed of 12,500 rpm for 30 min. After decanting the supernatant, the resulting gel was weighed. The analysis of the index was performed in at least 8 repetitions. The result was calculated according to the following Formula (1):

$$\text{WAI} = \frac{\text{mass of the gel}}{\text{mass of the sample}} \times 100\% \quad (1)$$

### 2.7. Evaluation of Water Solubility Index (WSI)

The Water Solubility Index (WSI) was determined using the method described by Harper [29]. The filtrate obtained from the determination of the Water Absorption Index (WAI) was dried to a constant weight at 110 °C, and its mass was then measured. The analysis of the index was conducted with a minimum of eight repetitions. The result was calculated using Equation (2):

$$\text{WAI} = \frac{\text{mass of filtrate after drying}}{\text{mass of the sample}} \times 100\% \quad (2)$$

## 2.8. Evaluation of the Expansion Ratio (ER)

The radial expansion ratio was calculated as the ratio of the extrudate diameter to the die diameter of the extruder, based on the methodologies of Makowska et al. [30]. The diameters of the extrudates were measured in 100 repetitions for each product.

## 2.9. Determination of Texture Parameters

Texture measurements were performed using the TPA (Texture Profile Analysis) test with a CT3 10 kg Texture Analyzer (Brookfield, Toronto, ON, Canada). The texture parameters of the product were evaluated using a cylindrical probe with a diameter of 38.1 mm and a length of 20 mm (TA 4/1000). Samples of 10 mm in length were cut from the extrudates. A double compression test was conducted with a minimum of 24 repetitions for each product. The following measurement conditions were applied [31,32]: threshold force value—5 g; compression distance—50% of the sample height; probe speed during the test—0.4 mm/s; speed before and after the test—1 mm/s.

## 2.10. Water Activity Assessment

The water activity assessment was performed using AquaLab 4TE device (Decagon Devices, Inc., Pullman, WA, USA), with an accuracy of  $\pm 0.0003$ , at a temperature of 293 K ( $20\text{ }^{\circ}\text{C}$ )  $\pm 2.5$  K. The measurement was conducted with a minimum of 8 repetitions.

## 2.11. Evaluation of Sorption Properties

### 2.11.1. Static-Desiccator Method

The evaluation of sorption properties was carried out using the static-desiccator method by determining sorption isotherms and establishing moisture equilibrium between the tested sample and an atmosphere of predetermined relative humidity, which was controlled using saturated salt solutions.

The equilibrium time for the system was set at 90 days, and the measurements were conducted within a water activity range of  $a_w = 0.07\text{--}0.98$  at a temperature of  $20\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$ . The test sample consisted of approximately 3 g of raw material or 1 g of the tested product, which was placed in a pre-weighed measuring vessel with a diameter of 15 mm and distributed in desiccators. Hygrostats with a water activity higher than 0.69 contained vessels with crystalline thymol to protect the tested product from microbiological spoilage. The equilibrium moisture content was determined based on the initial mass of the product and the increase or decrease in water content, allowing for the construction of sorption isotherms.

The empirical sorption isotherms were described based on the transformation of the Brunauer–Emmett–Teller (BET) model, considering the water activity range of  $0.07 \leq a_w \leq 0.33$ . The equation, characterized using the determination coefficient ( $R^2$ ), F-statistic values, and standard error of fit (FitStdErr), is expressed as follows (Equation (3)):

$$V = \frac{V_m C a_w}{(1 - a_w)[1 + (C - 1)a_w]} \quad (3)$$

where  $a_w$ —water activity (-),  $V$ —equilibrium moisture content (g  $\text{H}_2\text{O}/100$  g dry matter),  $V_m$ —monolayer moisture content (g  $\text{H}_2\text{O}/100$  g dry matter),  $C$ —energy constant.

The suitability of the model for describing the obtained adsorption isotherms was evaluated based on the analysis of the root mean square error (RMS), calculated using Equation (4):

$$\text{RMS} = \sqrt{\frac{\sum \frac{(m_{c_e} - m_{c_p})^2}{m_{c_e}}}{N}} \cdot 100 \quad (4)$$

where  $mc_e$ —empirical equilibrium moisture content (g H<sub>2</sub>O/100 g dry matter),  $mc_p$ —predicted equilibrium moisture content (g H<sub>2</sub>O/100 g dry matter),  $N$ —number of measurement points.

#### 2.11.2. Dynamic Method—Sorption Kinetics

The sorption kinetics of water vapor in the tested samples were determined using the dynamic method at a constant temperature of  $20\text{ °C} \pm 1\text{ °C}$  in environments with water activities of  $a_w = 0.55$  and  $a_w = 0.85$ . The measurement duration was 72 h, and mass changes were recorded continuously using a computer-based system at 5 min intervals. A sample of 0.5 g was placed on the balance pan for measurement.

#### 2.12. Statistical Analysis

The statistical analyses were performed using Statistica 13.3 (TIBCO Software Inc., Palo Alto, CA, USA). One-way analysis of variance and Tukey's post hoc test was performed to determine statistically homogenous subsets at  $\alpha = 0.05$ .

### 3. Results and Discussion

#### 3.1. Nutritional Value of Final Products

Based on the evaluation of fat content in extruded products enriched with hemp protein, it was found that the highest fat content was observed in the HP7 product (Table 2). At the same time, it was determined that, under the applied extrusion process parameters, an increase in hemp protein content did not lead to higher fat content in the HP2 and HP4 products. Assessing the fat content of extrudates with the addition of cricket powder, it was found that an increased proportion of powder resulted in higher fat content in the CP4 and CP7 extrudates. Moreover, products enriched with house cricket powder had higher fat content compared to those fortified with hemp protein. When evaluating the carbohydrate content in products enriched with hemp protein, it was found that as the amount of the additive increased, the carbohydrate content decreased, reaching its lowest level in the HP7 product. In the case of extrudates with CP, products enriched with 4% and 7% CP exhibited the lowest carbohydrate levels among all extruded products. The main goal of enriching snack products with hemp protein and house cricket powder was to increase the protein content in the produced extrudates. Among the products with added hemp protein, an increase in protein content was observed with the increasing amount of the additive, and all products in this group had a higher protein content compared to the reference product (R). Statistically significant differences were observed between HP2 and HP7. An increase in protein content with the use of hemp protein was also observed in the study by Radočaj [33] on gluten-free cracker fortification. The evaluation of protein content in products enriched with cricket powder showed that, similarly to products enriched with hemp protein, the introduced additive increased the protein content of corn extrudates. The highest protein content among all tested extrudates was observed in CP4 and CP7, while CP2 had a protein content like R. Based on the literature analysis, it was found that CP7 exhibited a protein content comparable to products containing 9% tuna fish meal [34] and similar to products with a 2–6% addition of spirulina powder [35]. At the same time, the protein content obtained for CP4 was higher compared to extrudates with a 5% addition of house cricket powder, as reported in the study by Igual et al. [36]. Referring to the literature studies by Norajit et al. [37] and Radočaj et al. [33], it was concluded that to achieve a high protein content (comparable to CP products) in snack products, the addition of hemp protein must be increased to 10–20%. The analysis of mineral compound content showed that their levels in extrudates, both HP and CP, increased with the growing amount of the applied additive, with a higher mineral compound content observed in HP. As indicated by

the literature data, hemp seeds and protein powder when isolated, are noted for their high mineral content, including magnesium, phosphorus, potassium, and iron [38,39]. However, cricket powder is also recognized for its rich mineral content, making it a valuable addition to various food products. Studies indicate that cricket powder is not only high in protein and fiber but also contains significant amounts of essential minerals such as iron, calcium, copper, phosphorus, and zinc [19]. This mineral profile enhances the nutritional value of foods, particularly in gluten-free and bakery products, where cricket powder can effectively address nutrient deficiencies [40]. Interestingly, no statistically significant differences were observed in the energy value of the enriched extrudates, both HP and CP.

**Table 2.** Nutrients and energy values of enriched extrudates with added 2%, 4%, and 7% hemp protein (HP) or cricket powder (CP) compared to the reference product (R).

Sample	Protein (g/100 g)	Fat (g/100 g)	Ash (g/100 g)	Carbohydrates <sup>1</sup> (g/100 g)	Energy Value <sup>2</sup> (kcal/100 g)
R	9.25 ± 0.48 <sup>c</sup>	2.11 ± 0.21 <sup>ab</sup>	1.55 ± 0.01 <sup>f</sup>	81.01	380
HP2	9.43 ± 0.51 <sup>bc</sup>	1.37 ± 0.14 <sup>c</sup>	1.66 ± 0.00 <sup>e</sup>	81.26	375
HP4	10.00 ± 0.60 <sup>b</sup>	1.67 ± 0.17 <sup>b</sup>	1.92 ± 0.01 <sup>b</sup>	80.43	377
HP7	10.94 ± 0.75 <sup>b</sup>	2.26 ± 0.23 <sup>a</sup>	2.17 ± 0.01 <sup>a</sup>	78.76	379
CP2	9.31 ± 0.89 <sup>c</sup>	2.05 ± 0.21 <sup>ab</sup>	1.65 ± 0.01 <sup>e</sup>	81.03	380
CP4	12.19 ± 0.95 <sup>ab</sup>	2.43 ± 0.24 <sup>a</sup>	1.73 ± 0.01 <sup>d</sup>	78.06	383
CP7	14.19 ± 0.81 <sup>a</sup>	2.55 ± 0.26 <sup>a</sup>	1.81 ± 0.01 <sup>c</sup>	78.32	385

<sup>1</sup> The carbohydrate content was estimated by subtracting the average content of ash, fat, and protein from 100%.

<sup>2</sup> Energy value was calculated based on the average moisture, protein, fat, and carbohydrate content. Mean values with the same letters in the column were not significantly different ( $\alpha = 0.05$ ).

Increasing the total protein and mineral content does not fully explain the improvement in the quality of the obtained extruded snack products. Therefore, their amino acid and mineral profiles were analyzed. The content of essential amino acids is a key parameter in assessing protein quality. These are amino acids that the human body cannot synthesize and must be obtained from food. Table 3 presents the amino acid profiles of the analyzed extrudates.

**Table 3.** Amino acid profiles in extrudates with added 2%, 4%, and 7% of hemp protein (HP) or cricket powder (CP) compared to the reference product (R).

Amino Acid (mg/g)	R	HP2	HP4	HP7	CP2	CP4	CP7
Essential amino acids							
Histidine	1.56 ± 0.27 <sup>e</sup>	1.58 ± 0.07 <sup>e</sup>	1.88 ± 0.12 <sup>d</sup>	2.27 ± 0.09 <sup>c</sup>	2.01 ± 0.08 <sup>cd</sup>	2.50 ± 0.04 <sup>bc</sup>	2.96 ± 0.05 <sup>a</sup>
Isoleucine	2.29 ± 0.06 <sup>e</sup>	2.49 ± 0.02 <sup>d</sup>	2.90 ± 0.11 <sup>cd</sup>	3.39 ± 0.13 <sup>cd</sup>	2.96 ± 0.03 <sup>cd</sup>	4.89 ± 0.08 <sup>b</sup>	6.63 ± 0.09 <sup>a</sup>
Leucine	8.83 ± 0.24 <sup>e</sup>	11.22 ± 0.48 <sup>cd</sup>	12.57 ± 0.29 <sup>c</sup>	12.57 ± 0.36 <sup>c</sup>	10.57 ± 0.07 <sup>d</sup>	13.81 ± 0.24 <sup>b</sup>	15.06 ± 0.14 <sup>a</sup>
Lysine	1.16 ± 0.44 <sup>d</sup>	1.11 ± 0.02 <sup>d</sup>	1.35 ± 0.06 <sup>d</sup>	1.86 ± 0.20 <sup>c</sup>	1.79 ± 0.03 <sup>c</sup>	2.32 ± 0.04 <sup>b</sup>	3.31 ± 0.05 <sup>a</sup>
Methionine	1.15 ± 0.10 <sup>d</sup>	1.23 ± 0.02 <sup>d</sup>	1.31 ± 0.05 <sup>c</sup>	1.69 ± 0.07 <sup>b</sup>	1.36 ± 0.01 <sup>c</sup>	1.75 ± 0.03 <sup>b</sup>	1.98 ± 0.04 <sup>a</sup>
Cysteine	0.38 ± 0.04 <sup>c</sup>	0.36 ± 0.06 <sup>c</sup>	0.34 ± 0.05 <sup>c</sup>	0.47 ± 0.01 <sup>b</sup>	0.29 ± 0.18 <sup>c</sup>	0.40 ± 0.01 <sup>b</sup>	0.60 ± 0.01 <sup>a</sup>
Phenylalanine	3.11 ± 0.09 <sup>c</sup>	3.60 ± 0.01 <sup>c</sup>	3.90 ± 0.13 <sup>b</sup>	4.64 ± 0.16 <sup>ab</sup>	3.59 ± 0.57 <sup>b</sup>	4.90 ± 0.10 <sup>ab</sup>	5.44 ± 0.06 <sup>a</sup>
Tyrosine	1.78 ± 0.01 <sup>d</sup>	2.09 ± 0.05 <sup>c</sup>	1.94 ± 0.11 <sup>c</sup>	2.47 ± 0.09 <sup>bc</sup>	2.00 ± 0.01 <sup>c</sup>	2.96 ± 0.07 <sup>b</sup>	3.64 ± 0.04 <sup>a</sup>
Threonine	2.12 ± 0.04 <sup>e</sup>	2.42 ± 0.02 <sup>d</sup>	2.67 ± 0.07 <sup>cd</sup>	3.13 ± 0.10 <sup>b</sup>	2.63 ± 0.02 <sup>cd</sup>	3.44 ± 0.05 <sup>b</sup>	4.04 ± 0.07 <sup>a</sup>
Valine	3.00 ± 0.16 <sup>cd</sup>	3.22 ± 0.11 <sup>cd</sup>	3.58 ± 0.12 <sup>c</sup>	4.18 ± 0.13 <sup>b</sup>	3.69 ± 0.03 <sup>c</sup>	4.77 ± 0.09 <sup>b</sup>	5.91 ± 0.18 <sup>a</sup>

Table 3. Cont.

Amino Acid (mg/g)	R	HP2	HP4	HP7	CP2	CP4	CP7
Non-essential amino acids							
Alanine	5.98 ± 0.18 <sup>c</sup>	6.05 ± 0.04 <sup>c</sup>	6.06 ± 0.16 <sup>c</sup>	6.75 ± 0.14 <sup>b</sup>	6.29 ± 0.04 <sup>bc</sup>	9.15 ± 0.13 <sup>a</sup>	10.97 ± 0.14 <sup>a</sup>
Arginine	2.65 ± 0.13 <sup>cd</sup>	2.35 ± 0.02 <sup>d</sup>	4.14 ± 0.11 <sup>a</sup>	4.52 ± 0.14 <sup>a</sup>	2.87 ± 0.04 <sup>c</sup>	3.62 ± 0.08 <sup>b</sup>	4.77 ± 0.04 <sup>a</sup>
Aspartic acid	4.48 ± 0.32 <sup>d</sup>	5.03 ± 0.06 <sup>cd</sup>	5.83 ± 0.06 <sup>c</sup>	6.98 ± 0.20 <sup>b</sup>	5.21 ± 0.04 <sup>cd</sup>	6.85 ± 0.12 <sup>b</sup>	8.11 ± 0.15 <sup>a</sup>
Glutamic acid	15.41 ± 0.56 <sup>d</sup>	17.46 ± 0.52 <sup>c</sup>	19.87 ± 0.53 <sup>b</sup>	21.05 ± 0.56 <sup>a</sup>	15.87 ± 0.21 <sup>d</sup>	21.11 ± 0.38 <sup>a</sup>	22.86 ± 0.42 <sup>a</sup>
Glycine	1.99 ± 0.15 <sup>c</sup>	2.31 ± 0.03 <sup>c</sup>	2.56 ± 0.10 <sup>a</sup>	3.24 ± 0.10 <sup>b</sup>	2.75 ± 0.02 <sup>c</sup>	3.89 ± 0.08 <sup>b</sup>	5.06 ± 0.08 <sup>a</sup>
Proline	6.09 ± 0.04 <sup>b</sup>	7.17 ± 0.17 <sup>a</sup>	7.25 ± 0.30 <sup>a</sup>	6.28 ± 0.07 <sup>b</sup>	6.33 ± 0.42 <sup>b</sup>	7.12 ± 0.15 <sup>a</sup>	7.36 ± 0.16 <sup>a</sup>
Serine	3.40 ± 0.06 <sup>c</sup>	3.68 ± 0.21 <sup>bc</sup>	4.08 ± 0.12 <sup>b</sup>	4.79 ± 0.15 <sup>a</sup>	3.68 ± 0.02 <sup>bc</sup>	4.86 ± 0.09 <sup>a</sup>	5.50 ± 0.05 <sup>a</sup>

The mean values marked with different letters in the rows differ statistically significantly at the level of  $\alpha = 0.05$ .

In the case of corn, lysine is the limiting amino acid, but threonine is also a limiting factor [41]. Increasing the total protein content may be a way to provide a greater amount of all amino acids, including the limiting ones. However, the additional amino acids supplied through food will not be properly absorbed. This is explained by Liebig's Law of the Minimum, which states that increasing the supply of nutrients does not ensure better absorption or faster growth if the demand for limiting nutrients is not met. Although this principle is typically applied in plant cultivation, it is often relevant to human nutrition as well [42–44]. The use of both additives increased the lysine content in corn extrudates, although house cricket powder proved to be a significantly better source of lysine. The higher the proportion of alternative proteins in the extrudates, the greater the amino acid content. However, the addition of 2% hemp protein did not improve the amino acid profile of the snack products. In contrast, the addition of 7% cricket powder increased the lysine content in the extrudates nearly threefold and the threonine content twofold. Significantly higher values were also observed for other essential amino acids (Table 3).

As reported by Montowska et al. [19], cricket powders are also an excellent source of nutritionally important mineral compounds. The analyzed commercial house cricket (*A. domesticus*) powders were found to be rich in iron, calcium, and magnesium, as well as zinc, manganese, and copper. The mineral composition of hemp protein is notable for its richness in essential minerals, which contributes to its nutritional value. Various studies have highlighted the significant presence of macro- and micronutrients in hemp seeds and their derivatives, such as hemp protein concentrates and flours [45–47]. Consequently, the changes in the mineral composition of the obtained extrudates were also examined, and the results are presented in Table 4.

As expected, the incorporation of both protein additives generally increased the content of the analyzed minerals. Hemp protein was found to be a better source of calcium than house cricket powder; however, in all variants of fortified extrudates, a significant increase in calcium content was observed compared to the control extrudates ( $p < 0.05$ ). Surprisingly, the addition of hemp protein also resulted in a greater increase in iron content in the final products. According to Smarzyński et al. [40], the inclusion of house cricket powder significantly increased the iron content in shortbread cookies, with the extent of enhancement proportional to the amount of cricket powder used. However, in the present study, no statistically significant changes in iron content were observed in the CP2 and CP4 variants containing cricket powder. This could potentially be attributed to a lower iron concentration in the cricket powder used in this study compared to values reported in the literature. Nevertheless, the highest level of insect protein supplementation led to an increase in iron content. A similar trend was observed for magnesium, where the extrudates supplemented with hemp protein exhibited a substantially greater increase in

magnesium content. In each case, extrudates containing hemp protein had nearly twice the magnesium content compared to those supplemented with cricket protein at the same inclusion level. Notably, sodium content also warrants attention. According to the existing literature, excessive sodium intake is a major contributor to the global rise in hypertension, prompting dietary recommendations to limit its consumption [48]. The addition of hemp protein resulted in a reduction in sodium content in the extrudates, which is particularly relevant from the perspective of hypertension prevention.

**Table 4.** Mineral profile of extrudates with added 2%, 4%, and 7% hemp protein (HP) or cricket powder (CP) compared to the reference product (R).

Minerals (mg/100 g)	R	HP2	HP4	HP7	CP2	CP4	CP7
Calcium (Ca)	2.37 ± 0.36 <sup>f</sup>	7.40 ± 0.06 <sup>d</sup>	13.06 ± 1.47 <sup>b</sup>	16.73 ± 0.61 <sup>a</sup>	5.07 ± 0.11 <sup>e</sup>	9.35 ± 0.08 <sup>c</sup>	12.37 ± 0.36 <sup>b</sup>
Potassium (K)	340.2 ± 70.8 <sup>b</sup>	335.2 ± 45.4 <sup>ab</sup>	372.3 ± 17.7 <sup>a</sup>	382.0 ± 22.1 <sup>a</sup>	301.4 ± 44.7 <sup>b</sup>	313.0 ± 60.1 <sup>b</sup>	346.5 ± 47.2 <sup>ab</sup>
Iron (Fe)	0.84 ± 0.01 <sup>c</sup>	1.07 ± 0.06 <sup>c</sup>	2.15 ± 0.08 <sup>b</sup>	3.13 ± 0.34 <sup>a</sup>	0.88 ± 0.04 <sup>c</sup>	0.82 ± 0.08 <sup>c</sup>	1.82 ± 0.26 <sup>b</sup>
Magnesium (Mg)	13.75 ± 0.50 <sup>f</sup>	32.01 ± 0.26 <sup>c</sup>	42.96 ± 1.33 <sup>b</sup>	59.93 ± 0.81 <sup>a</sup>	17.47 ± 1.93 <sup>e</sup>	20.19 ± 2.47 <sup>d</sup>	21.02 ± 0.85 <sup>d</sup>
Manganese (Mn)	0.15 ± 0.01 <sup>f</sup>	0.42 ± 0.01 <sup>c</sup>	0.71 ± 0.03 <sup>b</sup>	1.08 ± 0.01 <sup>a</sup>	0.19 ± 0.01 <sup>e</sup>	0.23 ± 0.00 <sup>e</sup>	0.32 ± 0.02 <sup>d</sup>
Copper (Cu)	0.25 ± 0.03 <sup>d</sup>	0.24 ± 0.01 <sup>d</sup>	0.31 ± 0.03 <sup>c</sup>	0.39 ± 0.01 <sup>c</sup>	0.22 ± 0.01 <sup>d</sup>	0.43 ± 0.01 <sup>b</sup>	0.56 ± 0.01 <sup>a</sup>
Zinc (Zn)	0.49 ± 0.03 <sup>d</sup>	0.90 ± 0.07 <sup>c</sup>	1.32 ± 0.05 <sup>b</sup>	2.21 ± 0.40 <sup>a</sup>	1.30 ± 0.04 <sup>b</sup>	1.43 ± 0.02 <sup>b</sup>	1.78 ± 0.09 <sup>a</sup>
Sodium (Na)	634.0 ± 22.5 <sup>a</sup>	533.94 ± 69.0 <sup>b</sup>	561.9 ± 49.1 <sup>b</sup>	571.2 ± 17.1 <sup>b</sup>	643.79 ± 19.6 <sup>a</sup>	666.28 ± 28.5 <sup>a</sup>	703.9 ± 12.8 <sup>a</sup>

The mean values marked with different letters in the rows differ statistically significantly at the level of  $\alpha = 0.05$ .

### 3.2. Color and Appearance of Enriched Extrudates

Color is one of the key factors determining consumers' choices of food products. Depending on the raw material used, it can lead to either a positive perception of the product, associated with providing aesthetic value to the consumer, or its rejection due to biases and preconceived notions about the product [49]. The color and appearance of an extruded snack product, which define its quality, can be influenced by the method of raw material processing, extrusion process parameters, and storage conditions of the final product [50]. Moreover, the color of extruded snack products also depends on the measurement location—whether it is taken from the outer surface or the cross-section of the product [37]. During the extrusion process of high-protein snacks, a decrease in the  $L^*$  parameter may occur, which is linked to Maillard reactions taking place during processing. Increasing the protein content in the mixtures used for their production may also lead to an increase in the  $b^*$  value, which corresponds to the presence of yellow tones in the product [50]. The color parameters of the extruded products are presented in Table 5, while the images of the obtained extrudates are shown in Figure S1. Based on the conducted colorimetric measurements, it was determined that among the analyzed extrudates, the lightest color was observed in R ( $L^* = 85.48$ ). This product also exhibited the lowest  $a^*$  parameter ( $-3.65$ ) and the highest  $b^*$  parameter ( $35.63$ ). Extrudates containing hemp protein and house cricket powder were characterized by a darker color, with an increased contribution of red tones and reduced yellow saturation. Moreover, these color changes were observed both in the ground form of the product and in the measurement of the external surface color, with an increasing amount of additive (Table 5, Figure S1). The darkest color was recorded in extrudates with the highest addition of hemp protein HP7 ( $L^* = 78.03$ ). Among the snack products containing house cricket powder, the highest  $a^*$  value ( $-1.16$ ) and the lowest  $b^*$  value ( $26.57$ ) were observed for CP7.

**Table 5.** Color parameters of enriched extrudates with added 2%, 4%, and 7% hemp protein (HP) or cricket powder (CP) compared to the reference product (R).

Sample	L*	a*	b*
R	85.48 ± 0.30 <sup>a</sup>	−3.65 ± 0.19 <sup>e</sup>	35.63 ± 0.05 <sup>a</sup>
HP2	81.46 ± 0.23 <sup>c</sup>	−2.88 ± 0.07 <sup>d</sup>	33.79 ± 0.05 <sup>b</sup>
HP4	80.47 ± 0.31 <sup>c</sup>	−2.75 ± 0.006 <sup>d</sup>	30.55 ± 0.08 <sup>c</sup>
HP7	78.03 ± 1.09 <sup>d</sup>	−2.24 ± 0.020 <sup>b</sup>	29.23 ± 0.02 <sup>c</sup>
CP2	83.55 ± 0.16 <sup>b</sup>	−2.50 ± 0.006 <sup>c</sup>	32.25 ± 0.06 <sup>b</sup>
CP4	81.23 ± 0.18 <sup>c</sup>	−2.12 ± 0.007 <sup>b</sup>	30.14 ± 0.05 <sup>c</sup>
CP7	79.72 ± 0.14 <sup>d</sup>	−1.16 ± 0.008 <sup>a</sup>	26.57 ± 0.09 <sup>d</sup>

The mean values marked with different letters in the columns differ statistically significantly at the level of  $\alpha = 0.05$ .

### 3.3. WAI, WSI and ER Results

The WAI is a parameter that characterizes the water-holding capacity of snack products and depends on the processing conditions and the moisture content of the raw materials. High WAI values may indicate the presence of large starch fragments in extruded products [51]. Furthermore, the WAI serves as a measure of the amount of gel formed by dispersed starch granules in excess water and is associated with the presence of significant amounts of hydrophilic groups as well as the porous structure of the extrudate [52]. A different role is attributed to the WSI. The WSI parameter reflects the intensity of transformations occurring during the extrusion process [51]. In highly processed products, the WSI value can reach up to 50%, which may indicate rapid digestion, intestinal absorption, and high postprandial blood glucose levels. According to Ding et al. [53], the WSI value is influenced by the type and physicochemical properties of the additives used, the moisture content of the raw materials, and the extrusion process parameters. Another crucial parameter for assessing the quality of corn extrudates is the expansion ratio (ER). This parameter defines the physical transformation resulting from water evaporation from the amorphous starch matrix at temperatures exceeding the glass transition point, provided that the material reaches an appropriate temperature during processing [7,54]. In extruded products, a higher expansion ratio corresponds to a greater number of voids (pores) within the product, which contribute to the desired texture and crispiness of the final extrudate. The expansion ratio is primarily influenced by extrusion process parameters, particularly the composition of the raw material mixtures used for snack production. A high protein content in extrusion mixtures often has an adverse effect, leading to reduced expansion and an undesirable extrudate structure [55].

The results of WAI, WSI, and ER measurements for the analyzed extrudates are presented in Table 6. Based on the research conducted, it was determined that among the products enriched with hemp protein, the highest values of the WAI were observed in HP4 (5.04 g/g) and HP7 (5.19 g/g). Moreover, an increase in the WAI was noted in the hemp protein-fortified products compared to the reference product (R), with WAI values rising in parallel with the increasing level of enrichment. A review of the literature revealed that the observed relationship contradicted the findings of Norajit et al. [37]. In their study, a decrease in the WAI was reported for rice extrudates as the content of defatted hemp powder increased. Similar trends, demonstrating a reduction in the hydrophilic properties of extrudates with increasing protein content, were also observed in studies by Szpendowski et al. [56] and Ruszkowska [57]. When evaluating the WAI in the group of products enriched with cricket powder, it was observed that the highest WAI values were recorded for CP2 (5.38 g/g) and CP4 (5.39 g/g). These values were higher compared to the WAI of products enriched with hemp protein. The incorporation of cricket powder led

to the formation of a starch–protein complex with an enhanced water retention capacity compared to products enriched with hemp protein and the reference sample. Among the products supplemented with *A. domesticus* powder, a decrease in the WAI was observed as the enrichment level increased, which contradicts the findings reported by Igual et al. [36]. It can be hypothesized that in the present study, increasing the cricket powder content in the mixture up to 7% may have resulted in a lower degree of starch gelatinization in the CP7 extrudate. This, in turn, could have directly contributed to the reduced WAI values observed in this product.

**Table 6.** Results of the Water Absorption Index (WAI), Water Solubility Index (WSI) and expansion ratio (ER) of extrudates with added 2%, 4%, and 7% hemp protein (HP) or cricket powder (CP) compared to the reference product (R).

Sample	WAI (g/g)	WSI (%)	ER (-)
R	4.86 ± 0.09 <sup>c</sup>	32.88 ± 2.14 <sup>a</sup>	3.64 ± 0.17 <sup>a</sup>
HP2	4.88 ± 0.10 <sup>b</sup>	30.15 ± 1.11 <sup>a</sup>	3.50 ± 0.18 <sup>a</sup>
HP4	5.04 ± 0.13 <sup>b</sup>	28.07 ± 1.60 <sup>ab</sup>	3.31 ± 0.17 <sup>b</sup>
HP7	5.19 ± 0.13 <sup>ab</sup>	26.70 ± 1.12 <sup>b</sup>	3.18 ± 0.13 <sup>c</sup>
CP2	5.38 ± 0.18 <sup>a</sup>	25.03 ± 2.18 <sup>b</sup>	3.40 ± 0.13 <sup>ab</sup>
CP4	5.39 ± 0.13 <sup>a</sup>	19.86 ± 1.15 <sup>c</sup>	3.13 ± 0.10 <sup>c</sup>
CP7	5.20 ± 0.17 <sup>a</sup>	12.90 ± 1.06 <sup>d</sup>	2.70 ± 0.12 <sup>d</sup>

The mean values marked with different letters in the columns differ statistically significantly at the level of  $\alpha = 0.05$ .

An additional parameter evaluated in the quality characterization of the extruded snack products enriched with hemp protein and cricket powder was the WSI. It was determined that R sample exhibited the highest WSI value among all produced snack products (Table 6). In the group of extrudates enriched with hemp protein, statistically significant differences in the WSI were observed among all tested samples. The higher the proportion of hemp protein (HP) used in the formulation, the lower the WSI values recorded. A similar effect of an enriching additive on the WSI in extruded products was reported by Norajit [37], who demonstrated a decrease in WSI due to an increased protein content in rice extrudates supplemented with defatted hemp powder. Similar dependencies have been observed for extrudates containing cricket powder. In this case as well, the higher the cricket protein content added, the lower the WSI values recorded. The analysis of the expansion ratio (ER) demonstrated that product R exhibited the highest ER value. The addition of HP and CP contributed to a reduction in the ER values of the produced snack products (Table 6). Moreover, it was observed that in all extrudate variants containing HP, the ER value was higher compared to snack products enriched with CP. Additionally, a higher protein content in the extrudate formulations was associated with lower ER values. An increase in protein content in extruded products may lead to a reduction in starch gelatinization, a phenomenon that has been extensively documented in the scientific literature [37,58,59].

### 3.4. Textural Parameters

The texture of extruded products results from the restructuring and retrogradation reactions of previously gelatinized and melted starch, as well as its interactions with proteins and lipids present in the matrix. The key quality attribute of snack products in terms of texture is multifaceted, encompassing characteristics such as fracturability, hardness, chewiness, and crispness. These attributes significantly influence consumer acceptance and preference, as evidenced by various studies that correlate instrumental measurements with sensory evaluations [60,61]. The results of the texture parameter

analysis indicated that products supplemented with hemp protein (HP) did not exhibit statistically significant differences in hardness between the first and second measurement cycles, with obtained values being lower than those of the reference product (R) (Table 7). In contrast, statistically significant differences were observed among products enriched with house cricket powder (CP). The lowest hardness values in the first (81.37 N) and second measurement cycles (32.16 N) were recorded for CP7, while CP2 and CP4 exhibited similar hardness levels. Furthermore, product R demonstrated the highest cohesiveness and springiness. Within the HP group, HP7 displayed the lowest cohesiveness. Similarly, among CP extrudates, the lowest cohesiveness and springiness were noted for the product with the highest supplementation level, i.e., CP7. Based on the results obtained, it can be inferred that cohesiveness and springiness were influenced by the type of protein used, with an increase in the enrichment level leading to a reduction in these parameters.

**Table 7.** Texture parameters of analyzed extrudates with added 2%, 4%, and 7% hemp protein (HP) or cricket powder (CP) compared to the reference product (R).

Sample	Hardness (N)	Hardness (2nd Cycle) (N)	Cohesiveness (-)	Springiness (mm)	Gumminess (N)	Chewiness (mJ)
R	88.61 ± 11.97 <sup>a</sup>	59.31 ± 16.28 <sup>a</sup>	0.09 ± 0.03 <sup>a</sup>	1.80 ± 0.22 <sup>a</sup>	8.24 ± 3.11 <sup>a</sup>	13.77 ± 6.05 <sup>a</sup>
HP2	80.93 ± 10.20 <sup>b</sup>	52.04 ± 10.57 <sup>b</sup>	0.08 ± 0.01 <sup>a</sup>	1.71 ± 0.24 <sup>a</sup>	6.26 ± 1.43 <sup>b</sup>	10.77 ± 3.57 <sup>ab</sup>
HP4	83.63 ± 9.49 <sup>b</sup>	48.69 ± 15.01 <sup>b</sup>	0.07 ± 0.02 <sup>b</sup>	1.49 ± 0.25 <sup>b</sup>	5.93 ± 2.27 <sup>b</sup>	9.26 ± 4.69 <sup>b</sup>
HP7	85.91 ± 9.85 <sup>ab</sup>	45.20 ± 12.75 <sup>bc</sup>	0.06 ± 0.02 <sup>b</sup>	1.35 ± 0.20 <sup>b</sup>	4.84 ± 1.60 <sup>c</sup>	6.85 ± 3.10 <sup>bc</sup>
CP2	90.27 ± 9.71 <sup>a</sup>	49.38 ± 14.06 <sup>b</sup>	0.06 ± 0.02 <sup>b</sup>	1.36 ± 0.25 <sup>b</sup>	5.32 ± 1.99 <sup>b</sup>	7.64 ± 4.00 <sup>b</sup>
CP4	85.68 ± 7.15 <sup>ab</sup>	48.72 ± 9.91 <sup>b</sup>	0.05 ± 0.01 <sup>b</sup>	1.25 ± 0.13 <sup>b</sup>	4.27 ± 0.99 <sup>c</sup>	5.31 ± 1.42 <sup>c</sup>
CP7	81.27 ± 12.57 <sup>b</sup>	33.13 ± 10.33 <sup>c</sup>	0.03 ± 0.01 <sup>c</sup>	0.83 ± 0.16 <sup>c</sup>	2.17 ± 0.74 <sup>d</sup>	1.96 ± 1.01 <sup>d</sup>

The mean values marked with different letters in the columns differ statistically significantly at the level of  $\alpha = 0.05$ .

### 3.5. Sorption Properties of Enriched Snacks

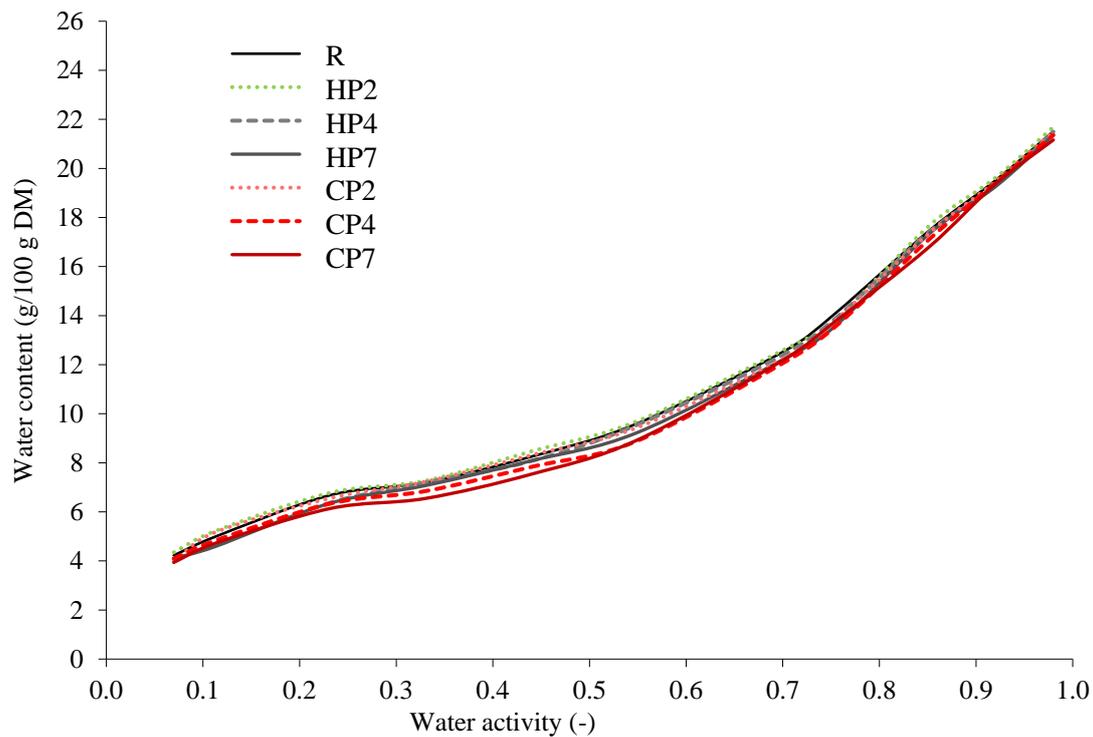
Water content and water activity are critical parameters that influence the quality and storage stability of food products. Their role is particularly significant in extruded snack products, as they directly affect crispness and structural properties. These characteristics are primarily determined by the composition of the processed mixture as well as the conditions of the extrusion process. In extruded products, a rapid decline in quality—specifically, a loss of crispness—is commonly observed once the threshold water activity ( $a_w$ ) value of 0.40 to 0.55 is exceeded, which typically corresponds to a moisture content of 8–10% [62]. The water content and water activity are presented in Table 8.

**Table 8.** Results of water content and water activity of analyzed extrudates with added 2%, 4%, and 7% hemp protein (HP) or cricket powder (CP) compared to the reference product (R).

Sample	Water Content (g/100 g DM)	Water Activity (-)
R	6.08 ± 0.01 <sup>b</sup>	0.2130 ± 0.009 <sup>a</sup>
HP2	6.29 ± 0.02 <sup>a</sup>	0.2068 ± 0.009 <sup>b</sup>
HP4	5.98 ± 0.04 <sup>b</sup>	0.2009 ± 0.008 <sup>c</sup>
HP7	5.87 ± 0.06 <sup>c</sup>	0.2058 ± 0.009 <sup>b</sup>
CP2	5.93 ± 0.02 <sup>b</sup>	0.2010 ± 0.009 <sup>c</sup>
CP4	5.58 ± 0.01 <sup>d</sup>	0.1974 ± 0.015 <sup>d</sup>
CP7	5.13 ± 0.04 <sup>e</sup>	0.1736 ± 0.012 <sup>e</sup>

The mean values marked with different letters in the columns differ statistically significantly at the level of  $\alpha = 0.05$ .

However, extruded snack products, due to their porous structure and, consequently, their large sorption surface area, exhibit high hygroscopicity. The packaging of extruded snacks significantly influences their moisture content during storage, primarily through the material's permeability and the environmental conditions. Studies indicate that the choice of packaging can either mitigate or exacerbate moisture absorption, affecting the product's quality over time [63,64]. The characterization of the sorption properties of extruded products, through the determination of sorption isotherms, allows for the identification of optimal processing and storage conditions. Figure 1 presents the sorption isotherms of the analyzed enriched snack products containing hemp protein (HP) and cricket powder (CP).



**Figure 1.** Sorption isotherm of extrudates with added 2%, 4%, and 7% hemp protein (HP) or cricket powder (CP) compared to the reference product (R).

Sorption isotherms describe the three-range process of sorption: the first stage represents the sorption process in the monomolecular layer ( $a_w = 0.07\text{--}0.44$ ), the second stage characterizes the multilayer sorption process ( $a_w = 0.55\text{--}0.75$ ), and the third stage corresponds to the capillary condensation process ( $a_w = 0.85\text{--}0.98$ ). Based on the graphical analysis of the sorption isotherms, the obtained curves exhibited a sigmoidal shape, showing similarity to type II isotherms according to the classification proposed by Brunauer et al. [65]. The sorption isotherms of the analyzed enriched snack products were continuous across the entire range of water activity ( $a_w = 0.07\text{--}0.98$ ). Evaluation of the sorption isotherms indicated that within the water activity range of  $a_w = 0.07\text{--}0.11$ , desorption occurred in all enriched extrudates as well as in the reference product. Further analysis of the relative positioning of the sorption isotherms revealed differences in hygroscopicity among the products, depending on the type of protein additive used—HP or CP. In the isotherm range ( $a_w = 0.23\text{--}0.44$ ), among the HP-enriched products, the highest hygroscopicity was observed for HP2. In the second range of the sorption isotherm, describing the multilayer sorption process, the highest hygroscopicity among the HP-enriched products was recorded for HP2 and HP4. In the isotherm range corresponding to capillary condensation ( $a_w = 0.85\text{--}0.98$ ), HP2 exhibited the highest equilibrium moisture content. A comparison of the equilibrium moisture content of the HP-enriched products with the reference product

(R) demonstrated that the reference product had higher hygroscopicity. However, higher equilibrium moisture content in the reference product compared to HP2 was observed only at a water activity of  $a_w = 0.75$ . The evaluation of the sorption isotherm determined for extrudates enriched with CP revealed that in the water activity ranges of  $a_w = 0.23$ – $0.44$  (Region I) and  $a_w = 0.55$ – $0.75$  (Region II), the highest hygroscopicity was observed for CP2. Based on the analysis of the sorption isotherm in the third region ( $a_w = 0.85$ – $0.98$ ), a decrease in product hygroscopicity was noted with increasing cricket powder content. In the capillary condensation region, similar to products enriched with hemp protein, the highest hygroscopicity was exhibited by the product with the lowest CP addition (CP2). A comparison of equilibrium moisture contents between CP-enriched products and the reference extrudate (R) indicated that CP2 attained higher equilibrium moisture content than R, at water activity levels of  $a_w = 0.11$  and  $a_w = 0.33$ – $0.44$ . Moreover, the equilibrium moisture content values obtained for CP-enriched products did not exceed those recorded for HP2 at any of the tested water activity levels. Analyzing the literature on the subject, it was found that the obtained sorption isotherms exhibited a similar course to those determined for expanded products made from millet groats and amaranth, protein-enriched extrudates containing soy and whey protein preparations, as well as extruded products investigated in studies conducted by other authors [66–69].

To determine the magnitude of selected surface microstructure parameters, the experimentally obtained sorption isotherms of the products were transformed according to the Brunauer–Emmett–Teller (BET) model, similarly to the assessment of the sorption properties of the raw material, within the water activity range of  $a_w = 0.07$ – $0.33$ . The monolayer capacity ( $v_m$ ), along with the other BET equation parameters—namely, the energy constant ( $c_e$ ) and the sum of squared deviations between theoretical and empirical values (SKO)—are presented in Table 9.

**Table 9.** BET equation parameters and specific surface area of extrudates with added 2%, 4%, and 7% hemp protein (HP) or cricket powder (CP) compared to the reference product (R).

Parameter	R	HP2	HP4	HP7	CP2	CP4	CP7
$v_m$ (g/100 g s. m.)	6.5701	6.6573	6.4859	6.5861	6.4648	7.0441	7.4084
$c_e$	4.2141	3.9326	4.6005	4.5714	4.4087	4.0065	3.8913
$R^2$	0.9579	0.9503	0.987	0.9806	0.9428	0.9604	0.946
SKO	7.1956	9.6893	3.9066	3.7537	3.3200	3.1295	5.3608
RMS (%)	8.0902	10.2447	5.0374	4.6872	3.8254	3.5211	5.2514
SSA (m <sup>2</sup> /g)	230.83	233.9	227.88	231.4	227.14	247.49	260.29

$v_m$ —monolayer capacity;  $c_e$ —energy constant values;  $R^2$ —determination coefficient; SKO—sum of squared deviations of the theoretical from empirical values; SSA—sorption surface area.

Based on the assessment of the monomolecular layer capacity in a group of products enriched with hemp protein, it was determined that the highest monolayer capacity ( $v_m$ ) was observed in HP2. Increasing the proportion of hemp protein in the formulation of extrudates did not lead to further surface development of the products. A comparison between the results of hemp protein-enriched snack products and the reference product revealed that HP2 and HP4 exhibited higher monolayer capacity ( $v_m$ ) values compared to R. Within the group of products enriched with CP, CP4 and CP7 demonstrated the highest monolayer capacity, suggesting that these products may possess the greatest storage stability. This assumption is based on the fact that a significantly expanded monomolecular layer surface protects food products from quality deterioration due to moisture absorption [70]. The product with the lowest CP addition exhibited the lowest  $v_m$  values within the CP group. Furthermore, the values obtained for this product were lower compared to the R product,

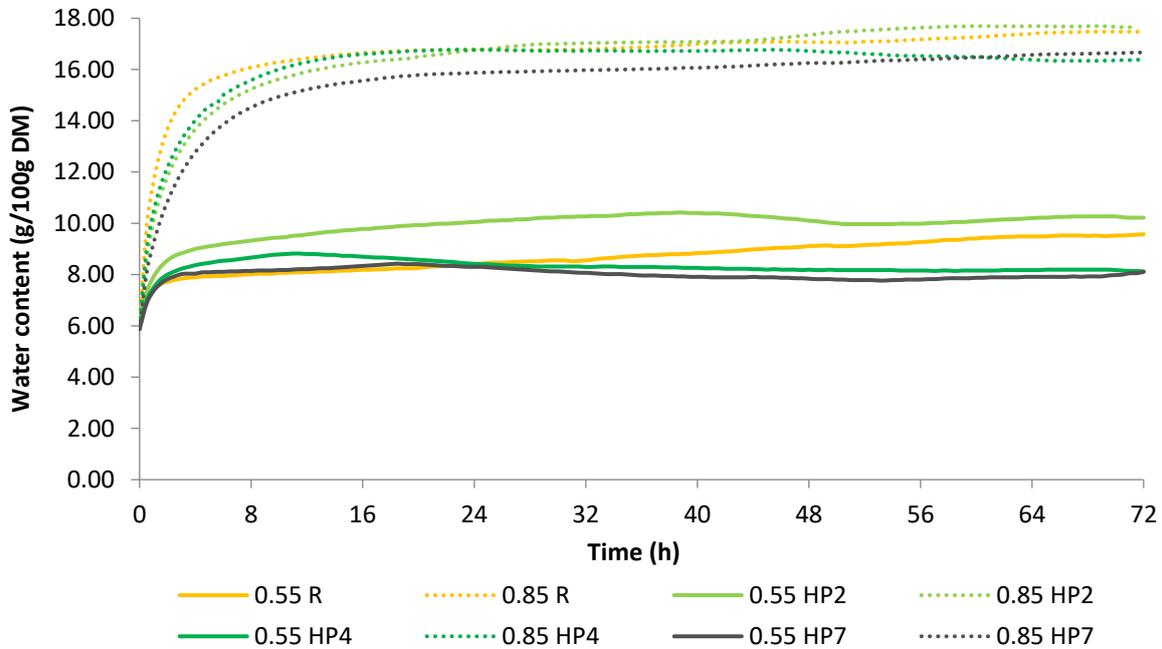
indicating that the incorporation of a 2% CP addition into the product formulation did not contribute to the development of monolayer capacity. A comparison of the monolayer capacity values among products enriched with hemp protein, cricket powder, and the base product revealed that CP4 and CP7 exhibited the highest monolayer capacity among all analyzed samples. Based on the determined monolayer capacity, it can be hypothesized that the studied products differed in the presence of hydrophilic groups capable of water binding, likely influenced by protein content and the structural properties of the starch–protein matrix formed during the extrusion process. During the extrusion of enriched snack products, proteins may act as a source of macromolecules rich in polar sites [70]. However, they are also attributed with the role of preventing complete starch degradation [66]. This suggests that during the extrusion process of enriched snack products, some crystalline regions within the starch structure were preserved, which demonstrate a relatively high resistance to hydration effects [71]. The next parameter determined in the BET equation was the energy constant  $c_e$ , which defines the amount of heat released during the sorption processes. The analysis conducted revealed that among the products containing HP, the highest value of this constant was observed in HP4. In the group of products enriched with CP, a decrease in the energy constant was noted with an increasing amount of the enriching additive. The evaluation of the obtained energy constant values ( $c_e$ ) suggests that only the process of physical sorption was observed during the storage of corn extrudates. Moreover, the values obtained for the tested raw materials ( $c_e > 2$ ) confirmed the sigmoidal shape of the sorption isotherm [72].

Based on  $v_m$ , the specific surface area of sorption (SSA) was calculated. The specific surface area of sorption, defined as the surface area per unit mass ( $\text{m}^2/\text{g}$ ), is one of the key parameters characterizing the ability of adsorbents to adsorb gases, vapors, and ions [66,73]. Based on the surface structure assessment (Table 9) of the group of extruded products enriched with hemp protein (HP), it was found that the highest specific sorption surface area was observed for HP2. Increasing the HP content in extrudates to 4% or 7% did not result in a further increase in specific sorption surface area. A comparison of the obtained specific sorption surface area values between R and HP products revealed that the products enriched with hemp protein exhibited similar specific sorption surface area values to the R product. Characterizing the surface structure of CP-enriched products revealed that the specific surface area (SSA) increased with the increasing amount of additive. The highest SSA values, exceeding those obtained for R and HP-enriched products, were observed in CP4 and CP7. In contrast, CP2 exhibited the lowest SSA among all the extruded product variants (Table 9). Based on the SSA values of HP- and CP-enriched products, it was determined that the specific surface area, as a derivative of the monolayer capacity, was influenced by the properties of the newly formed extrudate structure, which emerged during the extrusion process, as well as by the interactions between starch and protein molecules. A review of the literature indicated that the examined extrudates displayed higher SSA values compared to other enriched corn extrudates, bread, flavored fibers, and pasta [35,57,74].

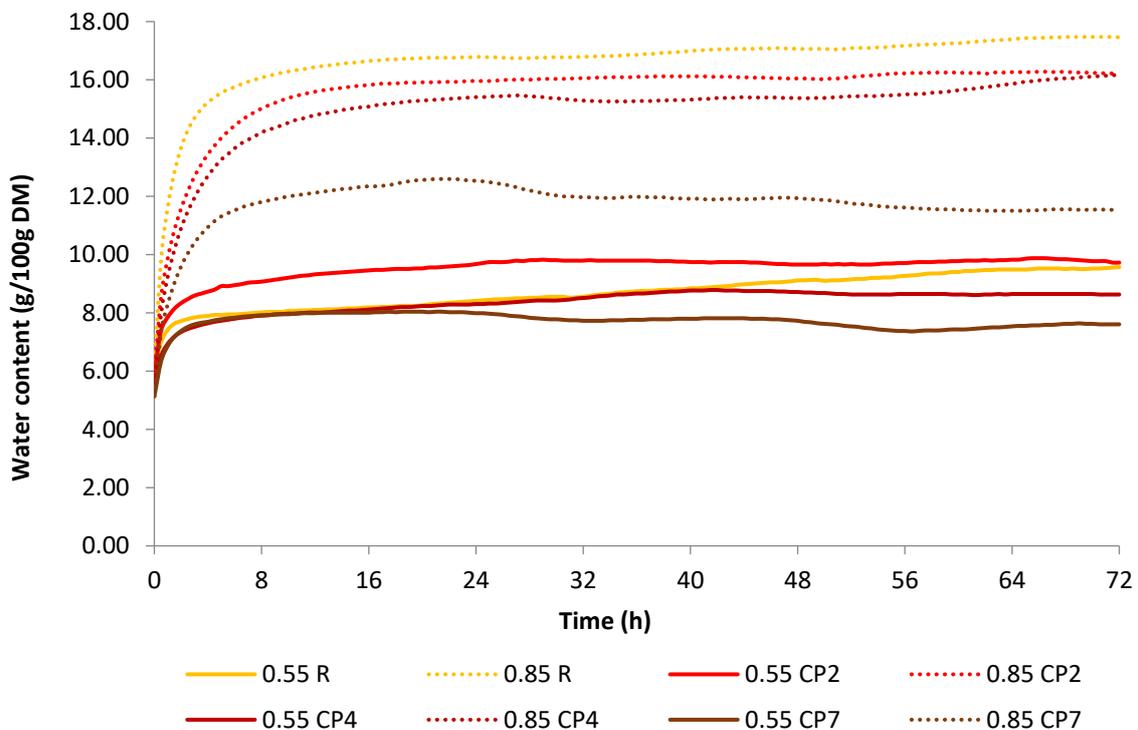
### 3.6. Kinetics of the Sorption Process

An essential aspect of this study was the evaluation of sorption kinetics, determined using a dynamic method. Sorption kinetics describes the rate at which the sorption process occurs. The application of dynamic water vapor sorption measurements, as opposed to the static desiccator method, allows for a significant reduction in analysis time and enables the assessment of multiple factors influencing the sorption rate [75,76]. In the case of extruded products and snack foods, the kinetics of the sorption process is of particular importance due to the rapid rate of storage-related changes, especially in terms of texture modifications

under increased ambient humidity. The changes in the moisture content of extrudates exposed to high relative humidity occur most intensively during the first 8–10 h of the process, while the extrudate’s moisture content stabilizes after 23–25 h, regardless of the conditions [77,78]. The sorption kinetics of the enriched corn extrudates are presented in Figures 2 and 3. The sorption kinetics measurements were conducted in two environments with water activities of  $a_w = 0.55$  and  $a_w = 0.85$ , at a temperature of 20 °C, over a period of 72 h.



**Figure 2.** Kinetic curve of extrudates with added 2%, 4%, and 7% hemp protein (HP) compared to the reference product (R) at water activity of  $a_w = 0.55$  and  $a_w = 0.85$ .



**Figure 3.** Kinetic curve of extrudates with added 2%, 4%, and 7% cricket powder (CP) compared to the reference product (R) at water activity of  $a_w = 0.55$  and  $a_w = 0.85$ .

In an environment with lower water activity ( $a_w = 0.55$ ), the highest water sorption capacity, and thus, the greatest hygroscopicity, was observed for HP2. Lower hygroscopicity was recorded for HP4 and HP7. Based on the kinetics of the sorption process, it was determined that water sorption in HP-enriched products proceeded most rapidly during the first 8 h of the process, confirming the findings of Gondek et al. [78] and Ekielski et al. [77]. During this initial period, HP-enriched products absorbed more than 80% of the total water mass adsorbed throughout the entire 72 h sorption process. A comparison between HP-enriched products and the reference product revealed that HP-enriched samples exhibited a higher equilibrium moisture content (R) after 8 h of sorption kinetics measurement. However, this trend changed after 24 h of sorption. After 72 h, it was found that HP2 and R had the highest equilibrium moisture content.

A similar sorption kinetics pattern was observed in the extrudates containing CP at a water activity level of  $a_w = 0.55$ . The highest hygroscopicity was recorded for CP2. The evaluation of sorption kinetics within the group of CP-enriched products demonstrated a decrease in extrudate hygroscopicity with an increasing amount of the enriching additive (Figure 3). Based on the conducted sorption kinetics measurements, it was determined that the sorption process, similarly to the products containing HP, exhibited the highest rate of water uptake during the first 8–10 h. Within the initial 8 h, the extrudates absorbed more than 70% of the total water mass adsorbed during the entire sorption process (72 h). Among all enriched products (both HP- and CP-containing), the HP-enriched samples exhibited a higher water content after 8 h of exposure to an environment with  $a_w = 0.55$ . The analysis of sorption changes further revealed that, after 72 h at 20 °C, the HP-enriched products demonstrated a higher equilibrium water content.

The kinetics of the sorption process were also measured in an environment with higher water activity ( $a_w = 0.85$ ). Based on the determined sorption kinetics, it was observed that among the HP-enriched products (Figure 2), HP4 exhibited the highest hygroscopicity during the first 24 h of measurement. However, at 48 and 72 h, HP2 demonstrated the highest hygroscopicity. Similar to the environment with lower water activity ( $a_w = 0.55$ ), the sorption kinetics in hemp protein-enriched products at  $a_w = 0.85$  proceeded most rapidly within the first 8 h. During this period, the extrudates absorbed approximately 80–90% of the total water mass adsorbed over the entire 72 h sorption process.

The results of the kinetic sorption curve analysis indicate that the hygroscopicity of CP-enriched products in an environment with a water activity of  $a_w = 0.85$  decreased with an increasing content of the enriching additive (Figure 3). Similarly to extrudates with HP, the highest dynamics of the sorption process were observed within the first 8 h of measurement. During this period, the extrudates absorbed over 81% of the total water mass adsorbed throughout the sorption process. Characterizing the sorption kinetics in an environment with a water activity of  $a_w = 0.85$  in CP-enriched extrudates, it was found that CP2 exhibited the highest equilibrium moisture content at 48 and 72 h of measurement. However, the obtained moisture content was lower than that observed for R.

#### 4. Comparison of Effect of HP- and CP-Enrichment of Corn Snacks

This study demonstrated that the incorporation of hemp protein (HP) and cricket powder (CP) into extruded corn snacks significantly influenced their nutritional, textural, and physicochemical properties. The results highlight distinct advantages associated with each protein source. CP-fortified snacks exhibited a higher protein content and superior essential amino acid profile, particularly lysine and threonine, which are limiting amino acids in corn. In contrast, HP-enriched snacks provided higher levels of essential minerals, including calcium and magnesium, while reducing sodium content, which may be beneficial for health-conscious consumers. Snacks fortified with CP exhibited lower

expansion ratios and greater density, resulting in a firmer texture. In contrast, HP-enriched extrudates were more cohesive and elastic, potentially contributing to improved consumer acceptance in certain snack formulations. CP-enriched snacks exhibited higher WAI values, indicating an increased ability to retain moisture. However, the WSI decreased with higher CP content, which may influence digestibility and texture perception. HP, on the other hand, contributed to a more balanced water interaction profile. Both protein additives resulted in darker extrudates due to Maillard reactions during extrusion. CP contributed to a reddish-brown hue, while HP led to more pronounced yellow tones. These color changes could influence consumer perception and product acceptability. CP increased the sorption surface area and hygroscopicity, particularly at higher inclusion levels, potentially affecting the storage stability of the extrudates. HP-enriched products demonstrated a lower sodium content and a more controlled water activity profile, which may enhance shelf-life stability.

## 5. Conclusions

The findings of this study underscore the potential of both hemp protein and cricket powder as sustainable protein sources for snack fortification, each offering distinct advantages that can be tailored to specific nutritional and functional requirements. Based on the results, the optimal supplementation levels depend on balancing nutritional benefits and textural properties. A supplementation level of 7% hemp protein is recommended for enhancing protein and mineral content while maintaining desirable texture. For cricket powder, a 4% supplementation level is optimal to maximize lysine and essential amino acid content without excessively compromising texture. A combination of 4% hemp protein and 4% cricket powder may be beneficial for achieving a balanced nutrient profile, while mitigating undesirable changes in expansion, hardness, and cohesiveness. Future research should focus on refining formulations to enhance product appeal and optimize health benefits for diverse consumer groups. Additionally, further studies should explore adjustments to extrusion parameters to enhance product structure and sensory attributes.

**Supplementary Materials:** The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su17073097/su17073097/s1>, Figure S1: Photographs illustrating the appearance and cross-section of extrudates.

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