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Corn Extrudates Enriched with Health-Promoting Ingredients: Physicochemical, Nutritional, and Functional Characteristics

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Abstract: The objective of this study was to evaluate the effects of different types of powder additions on the properties of corn extrudates. The following ingredients, which are good sources of bioactive compounds, were used to substitute corn flour: legume protein sources (2% pea, 5% broccoli, and 5% lucerne), plants (15% beetroot and 15% rosehip), and condiments (2% chili, 2% turmeric, 2% paprika, and 2% basil). The total polyphenolic content (TPC) and antioxidant activity (AA) increased when the corn flour was replaced with the different types of ingredients. The highest TPC was found for rosehip followed by the beet, basil, and broccoli additions. Compared to the raw formulations, all the extrudates, except the rosehip extrudate, showed a decrease in the TPC ranging from 11 to 41%, with the smallest loss (11%) occurring for basil and the highest loss (41%) occurring for the control extrudate, respectively. The same observation was recorded for the AA. For the extrudate enriched with rosehip, the TPC and AA increased by 20% and 16%, respectively. The highest level of protein digestibility was in the corn extrudate with the pea addition followed by broccoli and lucerne. The extruded corn samples with condiment additions had a lower glycemic index than the control extrudate. This study demonstrated the potential for the production of gluten-free corn extrudates enriched with ingredients from different sources with improved nutritional properties, conferring also a natural color in the final extrudates.

Keywords: corn; extrudates; protein sources; condiments; plants; antioxidant capacity; phenolic compounds; glycemic index

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1. Introduction

The size of the extruded products market is constantly growing in the context of modern consumer habits [1]. The extruded products market is projected to grow from USD 53.2 (in 2022) to 77.7 billion (by 2029). During the COVID-19 pandemic, extruded products saw a higher demand than that during the prepandemic period, the global extruded products market share had a growth of 2.98% in 2020 as compared to 2019 (Market Research Report, 2022) [2].

Most of the extruded products available on the market are made from corn and rice flours, which are relatively high in sugars and are considered to be energy-dense as well as nutritionally poor foods [3]. In this context, natural ingredients rich in bioactive compounds can be added to formulations to improve the nutritional properties of extrudates [4]. Several researchers obtained bioactive-compound-enriched extrudates by combining cereals with legumes [5,6], fruits [1], or food by-products [7,8]. On the other hand, the use of these ingredients in cereal-based extrudates can modify the physical properties, leading to less expanded products [5,9–11]. In this regard, extrudates should be carefully assessed, as their physical properties are directly associated with the consumers' acceptability [12–14].

Extrusion is a short-time high-temperature technology where the final extrudate product is achieved through a combination of different unitary operations, such as heating, mixing, shearing, and forcing the material through a nozzle in one step [15]. Extrusion is a thermally efficient, low-cost, and sustainable process for obtaining new products with a low microbial load and longer shelf life. Extrusion technology is widely applied in the bakery industry to develop various types of ready-to-eat products, such as breakfast cereals, instant products, flakes, snacks, puff pastries, textured vegetable proteins, textured animal proteins, products for pets, and others [16].

During extrusion, exposure to the simultaneous combined effects of a high temperature, a high pressure, and shearing leads to different types of reactions and changes in the nutritional and functional characteristics of the foods. These include starch gelatinization and dextrinization, protein denaturation, the inactivation of some antinutritional factors (trypsin inhibitors, chymotrypsin inhibitors, tannins, and phytates), a reduction in the microbial load, Maillard browning, and changes in the bioactive compounds and antioxidant properties. In addition to the nutritional profile, the properties of the extrudates are also affected by the processing parameters, namely the screw speed, the feed rate, and the raw material moisture [17–19]. Bisharat et al. [20] showed that the phenolic content and antioxidant activity of broccoli-enriched extrudates increased with the extrusion temperature and the broccoli powder addition and decreased with the moisture content of the mixture before extrusion.

The extrusion process has also been extensively studied to improve the protein and starch digestibility, nutritional properties, antioxidant activity, and functional activity of extruded products [21,22]. The optimization of the extrusion process is the essential step to develop extrudates with a higher level of bioactive compounds and an enhanced antioxidant potential [23].

The use of nutritional ingredients in the production of extrudates with good physical properties and sensory characteristics represents a great challenge. The chemical composition of the ingredients, especially the fiber and the protein content, affects the texture, expansion ratio, bulk density, and consumer acceptance of the extruded products [24].

With the aim to improve the nutritional value of corn-based extrudates, this study evaluated the effect of enrichment with different types of ingredient powders (namely, peas, broccoli, lucerne, beetroot, rosehip, chili, turmeric, paprika, and basil, respectively) on the nutritive, functional, physicochemical, and sensory properties as well as on the total phenolic content, antioxidant activities, and glycemic index of the corn extrudates. Besides these properties, the ingredients used gave a natural color in the final extrudates, which could play an important role in consumer attraction and acceptability as well as in the marketability of the gluten-free extruded food products.

2. Materials and Methods

2.1. Chemical Reagents

Folin–Ciocalteu's phenol reagent, gallic acid, Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid), DPPH (2,2-diphenyl-1-picrylhydrazyl), α-amylase (from porcine pancreas, 110 U, type I-A, saline suspension), trypsin (type IX-S), and methanol were acquired from Sigma–Aldrich (Saint Louis, MO, USA), whereas sodium carbonate was obtained from Carl Roth (Karlsruhe, Germany).

2.2. Raw Materials

Gluten-free corn flour was purchased from Probio (Staré Město, Czech Republic). The following powders were purchased from Paradisul Verde Inc S.R.L. (Brasov, Romania): pea protein, broccoli, lucerne, beetroot, rosehip, and turmeric. Chili, paprika, and basil were acquired from S.C. All for Nature S.R.L. (Timisoara, Romania), S.C. Solaris Plant S.R.L. (Bucharest, Romania), and Dary Natury Sp. Z.o.o (Grodzisk, Poland).

2.3. Formulations and Extrusion Process

Extrusion formulations were based on corn flour. Different types of powders and percentages were used to substitute the corn flour. The powders were from legume protein sources (2% pea, 5% broccoli, and 5% lucerne), plants (15% beetroot and 15% rosehip), and condiments (2% chili, 2% turmeric, 2% paprika, and 2% basil). The different percentages were chosen based on preliminary experiments.

Corn flour and each of the powders were mixed using a DomoClip laboratory mixer (Mundolsheim, France) at speed 7 for 20 min, were placed into plastic bags, and were kept overnight before extrusion. The final moisture of the mixtures was 12%.

The different mixtures were extruded using a single-screw laboratory extruder (Kompakt extruder KE 19/25 D, Brabender, Duisburg, Germany) with the following parameters: screw diameter of 19 mm, length/diameter ratio of 25:1, screw compression ratio of 3:1, 4 heating zones (50–100–140–140 °C), die diameter of 4 mm, screw speed of 100 rpm, and feeding speed of 20 rpm. The extruded samples were cooled at room temperature for 2 h and were stored in plastic bags for further analysis. The corn extrudates with different powders were labelled as follows: E_control (for the extrudate with 100% corn flour), E_pea, E_broccoli, E_lucerne, E_beet, E_rosehip, E_chili, E_turmeric, E_paprika, and E_basil. The appearance of the extrudates is shown in Figure 1. For further analysis, the extrudates were ground in a mill (MultiDrive control, IKA, Staufen, Germany) to form powder.

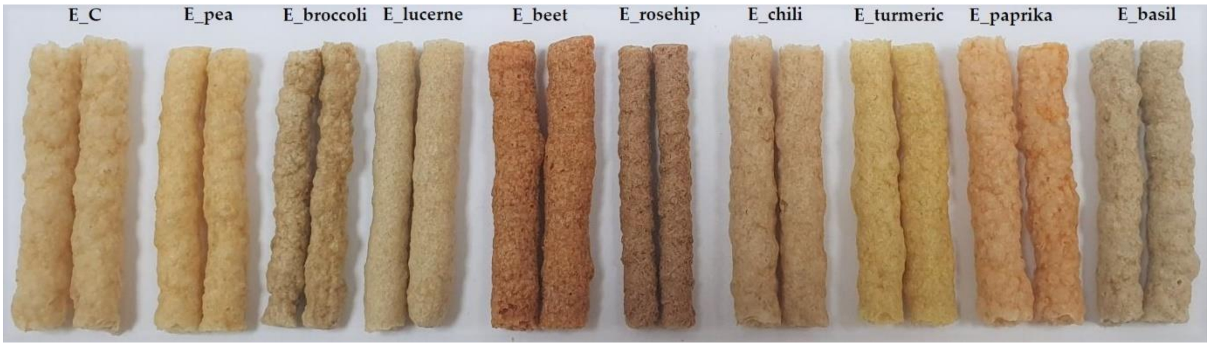

Figure 1. Appearance of the corn extrudates with different powders additions (two extrudates from each type).

2.4. Proximate Analysis of Extrudates

The milled extrudate samples were analyzed for nutritional composition using the AOAC procedures [25]. The protein content of the samples (N × 6.25) was determined using the Kjeldahl method using the Kjeltec™ 2300 mineralization–distillation unit (Foss Analytical, Höganäs, Sweden); fat was analyzed by extracting a known weight of the sample with petroleum ether using a Soxhlet apparatus (Soxtec™ 2055, Foss Analytical, Höganäs, Sweden); and the ash content was determined through calcination at 550 °C in a muffle furnace (type L 9/13, Nabertherm, Lilienthal, Germany). Total fiber content of the samples was determined using a total dietary fiber enzymatic assay kit (K-TDFR) following AOAC method 991.43 (Megazyme International Ltd., Bray, Ireland, 2000). Total carbohydrates were calculated by subtracting moisture, protein, ash, fat, and fiber content (%) from 100%, and the energy value was calculated using the conversion factors of 4 kcal/g for protein and carbohydrates, 9 kcal/g for fat, and 2 kcal/g for fiber, respectively [26]. All the chemical analyses were performed in triplicate.

2.5. Physical Properties

2.5.1. Expansion Ratio and Bulk Density

Expansion ratio (ER) of the extrudates was determined as the diameter of the extrudates divided by the diameter of the die nozzle (4 mm) [8]. The diameter of the extrudate samples was measured using a caliper (Vogel Germany, Kevelaer, Germany). Each value was an average of 10 measurements.

Bulk density (BD) of extrudates was calculated with the equation BD (g/cm^3) = $4m/\pi d^2 L$, where m is the mass of the extrudate (g), d is the diameter (cm), and L is the length (cm). The data reported were the means of 4 independent determinations.

2.5.2. Water Absorption Index and Water Solubility Index

The water absorption index (WAI) and water solubility index (WSI) were determined according to the method described by Medina-Rendon et al. [8]. Briefly, 2.5 g of milled extrudate was mixed with 25 mL distilled water in a tube, was shaken (Multi Reax Vortex, Heidolph Instruments, Schwabach, Germany) for 30 min, and was centrifuged at $6000\times g$ for 10 min (Eppendorf centrifuge 5804R, Hamburg, Germany). The supernatant was decanted into preweighed aluminum pans and was dried over night at 80 °C in an oven (Binder, Tuttlingen, Germany), and the sediment was weighed. WAI and WSI were calculated as follows:

WAI = weight of sediment/weight of extrudate

WSI (%) = (weight of dissolved solids in supernatant/weight of extrudate) × 100

2.5.3. Hardness

The hardness of the extrudates was measured using an Instron Texture Analyzer (model 5944, Illinois Tool Works Inc., Norwood, MA, USA) equipped with a load cell of 50 N. The samples were compressed with a cylinder probe of 3 mm diameter at a speed of 5 mm/min and at 5 mm distance. The curves of hardness vs. time were recorded automatically through the computer software Bluehill (version 3.13). Hardness (expressed in newtons) was the maximum force required to break the extrudate. Ten randomly extruded samples from each type were measured, and the hardness values recorded were averaged [8].

2.5.4. Color Measurement

A Minolta CM-5 model colorimeter (Konica Minolta Sensing, Inc., Osaka, Japan) coupled with SpectraMagic software was used for color measurement (L*, a*, and b* color coordinates). L* is the lightness coordinate, ranging from black (L* = 0) to white (L* = 100); a* coordinate is from greenness (a* < 0) to redness (a* > 0); and b* coordinate ranges from blueness (b* < 0) to yellowness (b* > 0). Black and white calibration plates were used to calibrate the instrument prior to color measurements. Color measurements were performed for the raw formulations and the extrudates and were expressed as an average of 10 readings. The total color difference (ΔE_1) was calculated according to the equation $\Delta E_1 = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$, where ΔL*, Δa*, and Δb* are the differences in L*, a*, and b*, respectively, between the control extrudate and the extrudates with different ingredients. In addition, the total color difference (ΔE_2) between the raw mixtures and the extrudates was calculated to assess the color changes of the mixtures caused by extrusion.

2.6. Differential Scanning Calorimetry

The gelatinization properties of the mixtures before extrusion and of the extrudate samples were determined with a differential scanning calorimeter (DSC 8000, PerkinElmer, Waltham, MA, USA). An amount of 10 mg of the samples was weighed in stainless steel pans suitable for the DSC 8000 equipment (60 µL, PerkinElmer, Waltham, MA, USA), and distilled water was added directly over the samples (water:flour mixtures/extrudates of 3:1). The pans were closed with a pressing system and were left for equilibration at room temperature overnight. Then, the samples were heated from 10 °C to 120 °C with a heat rate of 10 °C/min; the flush rate of nitrogen was 20 mL/min. Gelatinization peak temperature was recorded and calculated with help of the Pyris Manager software (PerkinElmer, Waltham, MA, USA).

2.7. Total Polyphenolic Content and Antioxidant Activity

A total of 1 g of the raw formulations (the mixtures before extrusion) or extruded samples was mixed with 6 mL of methanol (80%) at 1900 rpm and at room temperature for 3 h in a Multi Reax Vortex (Heidolph Instruments, Schwabach, Germany). The mixtures were centrifuged at 11,000 rpm for 30 min at 4 °C in an Eppendorf centrifuge (model 5804R, Hamburg, Germany). The fresh extracts were used for the measurement of the total polyphenolic content (TPC) and antioxidant activity and were adapted from Horszwald and Andlauer [27]. For quantification of TPC, the extracts (500 µL) were mixed with 5 mL of Folin–Ciocalteu's reagent (1:15), were incubated in dark for 10 min followed by addition of 500 µL of 20% sodium carbonate, and were left to react for 20 min in the dark. The absorbance was measured at λ = 755 nm (Specord 200 Spectrophotometer, Analytik Jena AG, Jena, Germany). Gallic acid was used as a standard for calibration with a concentration ranged between 0 and 0.175 mg/mL ($y = 7.5083 \cdot x + 0.0106$; $R^2 = 0.9999$). Analyses were carried out in triplicate, and data were reported as mean values expressed in terms of mg of gallic acid equivalents per 100 g of the sample dry matter basis (mg GAE/100 g d.m.).

For the antioxidant activity, the sample extracts (400 µL) were mixed with 6 mL of a methanolic DPPH solution (0.04 mg/mL), and the mixture was left in dark for 30 min. The absorbance was measured spectrophotometrically at λ = 517 nm. Trolox was used as a standard for calibration with a range of concentration from 0 to 0.6 mmol/L ($y = -1.9274 \cdot x + 1.1848$; $R^2 = 0.9996$). Analyses were carried out in triplicate. Results were expressed as mg of Trolox equivalent per 100 g of the sample dry matter basis (mg TE/g d.m.). The same methods were also used for the raw ingredients analysis, except the extraction procedure (i.e., 0.1 g of sample extracted with 30 mL of 80% methanol).

2.8. In Vitro Protein Digestibility

In vitro protein digestibility was performed based on the method described by Hsu et al. [28]. Briefly, extrudate samples were weighted, and distilled water was added in order to have an amount of 6.25 mg of protein/mL; then, the pH was set to 8.0 using 0.1 N NaOH. After incubation at 37 °C, the trypsin solution (1.6 mg/mL) was added to the suspension, and the pH value was read after 10 min. The percentage of protein digestibility was calculated according to the following equation: $\% = 210.46 - 18.10 \cdot pH$ [28].

2.9. In Vitro Starch Digestibility and Predicted Glycemic Index

The in vitro starch digestibility was measured using α-amylase following the procedure described by Germaine et al. [29]. The amount of reducing sugars released was measured spectrophotometrically at λ = 540 nm using the dinitrosalicylic acid method based on a standard curve of maltose. The hydrolysis curve was obtained as the amount of the reducing sugars released at different times (0–180 min). The predicted glycemic index (GI) was calculated from the hydrolysis index (HI) value of each sample. HI was calculated by dividing the area under the hydrolysis curves of the corn extrudate samples by the area obtained for a reference food (white bread). The GI was calculated using the equation described previously [30]: $GI = 8.189 + 0.862 \cdot HI$. Analyses were performed in triplicate.

2.10. Headspace–Electronic Nose Measurements

The overall volatile composition of the different corn extrudates was analyzed using an electronic nose system equipped with an array of 18 different metal oxide sensors and an HS100 autosampler (Alpha M.O.S., model FOX 4000, Toulouse, France). An amount of 0.5 g of ground extrudate was weighed, was placed in a 10 mL vial, and was hermetically sealed with a polytetrafluoroethylene/silicone septum. In order to generate the flavor compounds into the headspace, the vials were incubated for 900 s at 70 °C with stirring (250 rpm). Synthetic air and nitrogen were used as carrier gases with a flow of 150 mL/min. A volume of 2500 µL of the sample headspace was injected into the electronic nose system with an acquisition time of 120 s. All samples were run in triplicate, and the individual signals recorded were used for statistical analysis. For data processing, α-Soft version 8.0 software was used. Principal component analysis (PCA) was performed to detect the differences in the overall volatile composition among the extrudates.

2.11. Sensory Analysis of the Extrudates

Extrudate samples were assessed for sensory attributes, such as appearance, taste, hardness, and overall acceptability, using 30 trained panelists (65% were female, 35% were male, and the average age was 34 years old). Panelists rinsed their mouths with water after tasting each sample. A 9-point hedonic scale (from 1 = dislike extremely to 9 = like extremely) was used for the evaluation of the extrudates. The sensory evaluation study was approved by the Ethics Committee of the National Institute of Research and Development for Food Bioresources—IBA Bucharest.

2.12. Statistical Analysis

The data were analyzed through an analysis of variance (ANOVA) using Minitab software (version 19, Minitab Inc., Coventry, UK) to observe if there were significant differences between the results of the analyses. In order to compare the means of each analysis, Tukey's test was used, and the level of significance was considered to be less than 0.05 ($p < 0.05$).

3. Results

3.1. Proximate Composition of Extrudates

The results of the proximate analysis of the extrudates are presented in Table 1. The addition of legumes and plants (i.e., peas, broccoli, lucerne, beetroot, and rosehip) significantly increased ($p < 0.05$) the protein content of the corn extrudates compared to the control extrudate. Similar results were obtained in previous studies by adding different amounts of legumes [5,21]. The addition of condiments did not significantly change the protein content as compared to that of the control extrudate ($p > 0.05$). The addition of lucerne, beetroot, chili, turmeric, paprika, and basil, respectively, did not show a significant difference in the concentration of fat as compared to the control extrudate. A significant variation ($p < 0.05$) in the ash content of the extrudates was noticed depending on the percentage contribution of the added ingredient used in the corn flour substitution. Accordingly, the highest ash content was for E_beet and E_rosehip, where a percentage of 15% of the beetroot and rosehip powders, respectively, was used in the extrudate formulations. Similar to the ash content, the fiber content of the extrudates showed an increasing trend because the fiber content of the added ingredients was higher than that of corn. The fiber content of the rosehip- and beetroot-blended corn extrudates were 2- and 1.5-fold higher than that of the control extrudate. For the other extrudates, the fiber content values were between 1.1- and 1.3-fold higher. The energy values of the extrudates ranged from 349.8 to 359.7 kcal/100 g.

Table 1. Proximate composition of the different types of corn-based extrudates.

Sample	Protein (% d.m.)	Ash (% d.m.)	Fat (% d.m.)	Total Fiber (% d.m.)	Energy Value (kcal/100 g)
E_control	5.75 ± 0.01 ^{e}	0.57 ± 0.02 ^{f}	0.14 ± 0 ^{d}	6.73 ± 0.04 ^{f}	359.0 ± 0.16 ^{b}
E_pea	7.53 ± 0.02 ^{a}	0.82 ± 0.02 ^{d}	0.23 ± 0 ^{b}	6.88 ± 0.01 ^{f}	359.74 ± 0.08 ^{a}
E_broccoli	7.21 ± 0.02 ^{b}	0.84 ± 0.02 ^{d}	0.68 ± 0.02 ^{a}	8.59 ± 0.08 ^{c}	358.55 ± 0.04 ^{c}
E_lucerne	6.34 ± 0.19 ^{c}	0.95 ± 0.05 ^{c}	0.16 ± 0 ^{d}	8.64 ± 0.15 ^{c}	356.19 ± 0.11 ^{f}
E_beet	6.98 ± 0.05 ^{b}	1.60 ± 0.02 ^{a}	0.14 ± 0.01 ^{d}	9.72 ± 0.06 ^{b}	353.20 ± 0.13 ^{g}
E_rosehip	6.19 ± 0.01 ^{cd}	1.05 ± 0.01 ^{b}	0.23 ± 0.01 ^{bc}	13.11 ± 0.10 ^{a}	349.84 ± 0.13 ^{h}
E_chili	5.90 ± 0 ^{e}	0.75 ± 0.01 ^{de}	0.17 ± 0.02 ^{d}	7.46 ± 0.03 ^{de}	358.39 ± 0.08 ^{cd}
E_turmeric	5.75 ± 0.02 ^{e}	0.79 ± 0.03 ^{d}	0.18 ± 0.02 ^{cd}	7.23 ± 0.04 ^{e}	358.04 ± 0.09 ^{de}
E_paprika	5.97 ± 0.05 ^{de}	0.68 ± 0.02 ^{e}	0.18 ± 0.02 ^{bcd}	7.57 ± 0.03 ^{d}	358.25 ± 0.04 ^{cd}
E_basil	5.93 ± 0.02 ^{e}	0.77 ± 0.02 ^{de}	0.17 ± 0.01 ^{d}	7.48 ± 0.01 ^{de}	357.71 ± 0.04 ^{e}

Data presented as means ± standard deviations from triplicate analyses. Values followed by different superscript letters in the same column are significantly different ($p < 0.05$). d.m.: dry matter.

Compared to E_control, the energy value decreased with the substitution of the corn flour with different ingredients, except E_pea, where a small increase of 0.2% was obtained which is explained by the higher protein content. However, the highest decrease in the energy value was for E_rosehip (2.6%), while, for the others extrudates, the decrease was between 0.1 and 0.8%.

3.2. Extrudate Characteristics

3.2.1. Expansion Ratio and Bulk Density

The expansion ratio influences the fragility, bulk density, and softness of extrudates, playing a significant role in the consumers' acceptability [5,11]. The ER significantly increased ($p < 0.05$) from 2.19 to 2.43 when paprika was added to the corn flour (Table 2). The same effect was recorded for E_chili. E_turmeric, E_beet, and E_basil were not significantly different ($p > 0.05$) compared with E_control. On the other side, compared to the control extrudate, the ER significantly decreased ($p < 0.05$) when broccoli, rosehip, lucerne, and peas were added. Legume flours, with a high protein and fiber content, were reported to reduce the expansion ratio of the extrudates [5]. The lower expansion ratio for E_broccoli is in line with previous research, where a significant decrease in the expansion ratio of the corn extrudates was obtained when the corn flour was substituted with increasing levels of broccoli powder (4–10%), which bring a higher concentration of protein and fiber [10]. The decrease in the expansion ratio was attributed to the interaction between the proteins and fibers of broccoli and starch as well as to the strongly capacity of fiber to bind water compared to starch and to the fact that fibers can stop air bubbles to expand to the maximum level [5]. The expansion ratio correlated with the composition of the raw ingredients and with the interaction of starch, protein, and fiber. A lower fiber and protein content and a higher starch level result in higher product expansion [31]. For the investigated extrudates, a negative correlation was found between the protein content and the ER ($r = -0.5802$; $p < 0.05$) as well as between the fiber content and the ER ($r = -0.5139$; $p < 0.05$).

Table 2. Physical properties of the different types of corn-based extrudates.

Sample	ER	D (mm)	BD (g/cm^3)	Hardness (N)	WAI	WSI (%)
E_control	2.19 ± 0.04 ^{c}	8.78 ± 0.15 ^{c}	1.45 ± 0.14 ^{cdef}	8.83 ± 0.94 ^{d}	3.59 ± 0.01 ^{f}	18.01 ± 0.19 ^{c}
E_pea	1.90 ± 0.05 ^{e}	7.58 ± 0.20 ^{e}	1.58 ± 0.14 ^{bcd}	13.07 ± 1.94 ^{c}	6.60 ± 0.02 ^{a}	6.01 ± 0.02 ^{i}
E_broccoli	1.61 ± 0.06 ^{f}	6.44 ± 0.24 ^{f}	3.36 ± 0.10 ^{a}	26.07 ± 1.65 ^{a}	4.16 ± 0.08 ^{d}	7.86 ± 0.31 ^{h}
E_lucerne	2.03 ± 0.07 ^{d}	8.11 ± 0.28 ^{d}	1.50 ± 0.13 ^{cde}	13.11 ± 1.11 ^{c}	5.65 ± 0.06 ^{b}	10.59 ± 0.17 ^{g}
E_beet	2.27 ± 0.05 ^{bc}	9.06 ± 0.19 ^{bc}	1.70 ± 0.07 ^{bc}	7.87 ± 1.28 ^{de}	3.57 ± 0.01 ^{f}	19.53 ± 0.11 ^{b}
E_rosehip	1.70 ± 0.08 ^{f}	6.80 ± 0.33 ^{f}	1.50 ± 0.11 ^{cde}	16.16 ± 1.67 ^{b}	3.00 ± 0.03 ^{g}	32.62 ± 0.11 ^{a}
E_chili	2.33 ± 0.07 ^{ab}	9.33 ± 0.29 ^{ab}	1.32 ± 0.05 ^{def}	6.97 ± 0.41 ^{ef}	3.61 ± 0.03 ^{f}	16.20 ± 0.12 ^{d}
E_turmeric	2.29 ± 0.08 ^{bc}	9.15 ± 0.33 ^{bc}	1.21 ± 0.13 ^{f}	7.43 ± 1.01 ^{def}	5.38 ± 0.11 ^{c}	13.01 ± 0.33 ^{e}
E_paprika	2.43 ± 0.08 ^{a}	9.70 ± 0.31 ^{a}	1.29 ± 0.07 ^{ef}	6.08 ± 0.57 ^{f}	3.65 ± 0.02 ^{f}	15.94 ± 0.32 ^{d}
E_basil	2.26 ± 0.06 ^{bc}	9.03 ± 0.24 ^{bc}	1.84 ± 0.10 ^{b}	7.56 ± 0.25 ^{def}	3.83 ± 0.03 ^{e}	11.45 ± 0.26 ^{f}

ER represents expansion ratio, BD represents bulk density, WAI represents water absorption index, and WSI represents water solubility index. Values are means ± standard deviations (n = 10 for ER, n = 4 for BD, n = 10 for hardness, and n = 3 for WAI and WSI). Values followed by different superscript letters in the same column are significantly different ($p < 0.05$).

E_broccoli had the lowest expansion ratio and the highest bulk density. The reduction in the expansion of the extrudates corresponded to an increase in the bulk density, as more extrudates could be compacted in a given volume [5,11]. A negative correlation between the expansion ratio and bulk density of the extrudates was observed ($r = -0.6454$; $p < 0.05$). Thus, lower values for the extrudates' expansion ratio and diameter resulted in extrudates with a higher bulk density.

The extrusion conditions and the type of ingredients used for extrusion are important factors for product expansion. For example, Singh et al. [11] showed a significant reduction in the expansion ratio of extrudates with the incorporation of beet powder, while no significant difference ($p > 0.05$) regarding the expansion ratio between the beetroot extrudate and the control was observed in this study.

The bulk density of the extrudates did not significantly differ ($p > 0.05$) from that of E_control, except E_broccoli and E_basil, which showed higher values. From the industrial production point of view, a low density is a desirable characteristic for extrudates since many products are packed by mass (weight) and not by volume [5].

3.2.2. Water Absorption Index and Water Solubility Index

The WAI and WSI (Table 2) show how extrudates interact with water and are significantly influenced by the raw materials and processing conditions [32]. The WAI shows the proportion of water absorbed by the extrudate when introduced to water and can be used as an indication of starch gelatinization. The WSI represents the water-solubilized components, and it is used as a measure of the degradation of the molecular components, reflecting the degree of starch degradation, and depends on the reactions that occur during extrusion [1,33].

Compared to the control extrudate, a significantly higher amount of water ($p < 0.05$) was absorbed by the extrudates containing peas, lucerne, turmeric, broccoli, and basil, respectively. The WAI of E_beet, E_chili, and E_paprika did not significantly differ ($p > 0.05$) from that of E_control. A significant decrease ($p < 0.05$) in the WAI was registered for the extrudate with a rosehip addition. This decrease might be attributed to starch melting (dextrinization), which prevailed over the gelatinization process [34].

The WSI values of the extrudates decreased when the ingredients from the legume and condiment sources were used to replace the corn flour. A lower value of the WSI means a reduction in the risk of potential molecular damage caused by water-solubilized molecules. Thus, the addition of peas, broccoli, lucerne, and condiments (chili, turmeric, paprika, and basil), respectively, to the corn flour resulted in a reduction in the solubilization of the matrix components during extrusion compared to the control corn extrudate. The extrudates with lower values of the WSI could be more stable [1]. Igual et al. [33] also showed that, for the extrudates obtained through a lucerne addition to the corn flour, the WAI increased and that the WSI decreased, determining less solubilization of the matrix components. In this study, the WAI was negatively correlated with the WSI ($r = -0.7103$; $p < 0.05$). This opposite trend is explained by the chemical composition of the different ingredients added, mainly fiber and protein. The addition of beetroot and rosehip led to a significant increase in the WSI ($p < 0.05$) that can be explained by the degradation of starch causing a decrease in the molecular mass and an increase in water-soluble substances. In addition, a positive correlation was found between the fiber content of the extrudates and the WSI ($r = 0.7642$; $p < 0.05$). This is in line with previous results which showed an increase in the WSI of corn extrudates as the fiber content increased through the addition of soy fiber [35] or mango peel flour [8].

3.2.3. Hardness

The hardness of extrudates represents the consumers' view and is associated with the expansion and cell structure of the product [36]. A highly negative correlation was found between the extrudates' diameter and hardness ($r = -0.9359$; $p < 0.05$) as well as between the expansion ratio and hardness ($r = -0.9361$; $p < 0.05$); thus, lower expansion corresponds to harder extrudates (Table 2). This is in agreement with previous results [8,37]. Moreover, the extrudates with a higher bulk density exhibited greater hardness ($r = 0.8348$; $p < 0.05$). Igual et al. [33] also related hardness to the bulk density of corn extrudates with different percentages of lucerne. The authors highlighted that hardness could be influenced by the protein and fiber content from the lucerne and that harder extrudates are the consequence of the strong adherence of protein and starch. In this study, a slightly positive correlation was noted between hardness and the protein content ($r = 0.5874$; $p < 0.05$), and a lower correlation was noted between hardness and the fiber content of the extrudates ($r = 0.3723$; $p < 0.05$). The hardest extrudate was E_broccoli followed by E_rosehip, E_lucerne, and E_pea ($p < 0.05$). The increase in the extrudates' hardness was accounted to the components of the mixtures that caused a lubricating effect on the melt, limiting starch gelatinization [11]. A minimum hardness value is desirable for extrudates. The lowest value of hardness was obtained for the extrudate with a paprika addition.

However, the extrudates with condiment additions presented the lowest hardness values among the other extrudates investigated.

3.2.4. Color Analysis

Color is an important attribute for extrudate products because the processing conditions contribute to the reaction between reducing sugars and amino acids, which leads to the generation of colored compounds [38]. Besides the formation of Maillard reaction products, the color is affected by the pigments from the raw ingredients [9,11,20,39].

The incorporation of the different types of ingredients significantly influenced the color parameters (L*, a*, and b*) of the extrudates ($p < 0.05$) (Table 3). The maximum lightness (L* value) was observed for the control corn extrudate, which decreased significantly ($p < 0.05$) when the corn flour was substituted with other ingredients. Thus, E_beet showed the lowest L* value (i.e., the darkest) as compared to the other extrudates ($p < 0.05$) followed by E_rosehip and E_paprika. Singh et al. [11] attributed the lower L* value of the corn extrudates with beetroot powder added to them to different browning reactions, such as caramelization and Maillard browning, which took place due to the presence of sugars in beets. Redness (a* value) was the highest for E_paprika and E_beet followed by E_rosehip due to the reddish color of the added powders. Compared to the control, the a* value presented a decrease for E_turmeric, E_broccoli, E_lucerne, and E_basil. The extrudate with turmeric had the highest yellowness (positive b* value) due to the presence of the turmeric powder [38].

Table 3. Color coordinates (L*, a*, and b*) of the extrudates and total color differences.

Extrudates	L*	a*	b*	ΔE_1	ΔE_2
E_control	75.61 ± 0.04 ^{a}	5.84 ± 0.01 ^{e}	22.89 ± 0.02 ^{e}	-	17.87 ± 0.04 ^{f}
E_pea	74.65 ± 0.06 ^{b}	6.86 ± 0.03 ^{d}	26.24 ± 0.03 ^{d}	3.64 ± 0.03 ^{h}	18.11 ± 0.07 ^{e}
E_broccoli	72.84 ± 0.05 ^{d}	3.40 ± 0.02 ^{g}	20.75 ± 0.04 ^{i}	4.27 ± 0.06 ^{g}	14.96 ± 0.06 ^{h}
E_lucerne	71.75 ± 0.02 ^{f}	2.43 ± 0.02 ^{h}	21.07 ± 0.04 ^{g}	5.46 ± 0.04 ^{f}	12.59 ± 0.03 ^{j}
E_beet	65.11 ± 0.03 ^{j}	14.03 ± 0.01 ^{a}	26.42 ± 0.03 ^{c}	13.78 ± 0.03 ^{b}	22.85 ± 0.04 ^{a}
E_rosehip	66.64 ± 0.04 ^{i}	8.10 ± 0.01 ^{b}	18.31 ± 0.03 ^{j}	10.32 ± 0.07 ^{d}	15.59 ± 0.04 ^{g}
E_chili	69.98 ± 0.02 ^{g}	7.19 ± 0.01 ^{c}	21.48 ± 0.02 ^{f}	5.96 ± 0.05 ^{e}	19.74 ± 0.02 ^{d}
E_turmeric	73.34 ± 0.05 ^{c}	3.65 ± 0.02 ^{f}	37.00 ± 0.11 ^{a}	14.46 ± 0.09 ^{a}	20.31 ± 0.06 ^{c}
E_paprika	69.88 ± 0.04 ^{h}	14.03 ± 0.03 ^{a}	28.98 ± 0.04 ^{b}	11.70 ± 0.04 ^{c}	21.98 ± 0.06 ^{b}
E_basil	72.06 ± 0.04 ^{e}	2.24 ± 0.03 ^{i}	20.85 ± 0.06 ^{h}	5.45 ± 0.03 ^{f}	14.10 ± 0.04 ^{i}

All data represent the means of ten determinations. Values followed by different superscript letters in the same column are significantly different ($p < 0.05$). L* represents lightness, a* represents red/green coordinate, b* represents yellow/blue coordinate, ΔE_1 represents color difference between the control extrudate and the extrudates with different ingredients, and ΔE_2 represents color difference between the raw formulations and the extrudates.

The color difference between the extrudates with ingredient additions and the control corn extrudate (ΔE_1) varied between 3.6 and 14.5, values which are greater than 3 and are thus perceptible to the human eye [33]. An increase in ΔE indicates greater color changes. The highest differences were recorded for E_turmeric, E_beet, E_paprika, and E_rosehip. ΔE_2 (which is the color difference before and after extrusion) showed higher values. This represents a darker color with more intense red and yellow colors [1,33]. These differences were higher for the samples with additions of beetroot, paprika, turmeric, chili, and peas, respectively, than for the control. On the other side, the samples with rosehip, broccoli, basil, and lucerne had lower ΔE_2 values than control. This was observed previously in the corn extrudates enriched with different types of rosehip powders [1].

3.3. Thermal Properties

The DSC analysis of the flour mixtures before extrusion showed an endothermic peak in the range of 71–75 °C (i.e., corn endothermic peak of 73.2 °C, corn–pea endothermic peak of 73.8 °C, corn–broccoli endothermic peak of 72.0 °C, corn–lucerne endothermic peak of 72.6 °C, corn–beetroot endothermic peak of 74.7 °C, corn–rosehip endothermic peak of 71.2 °C, corn–chili endothermic peak of 70.9 °C, corn–turmeric endothermic peak of 71 °C, corn–paprika endothermic peak of 71.8 °C, and corn–basil endothermic peak of 71.8 °C). This peak was not observed in all the extruded samples. A comparison between the DSC curve of the corn flour (before extrusion) and the DSC curve of the extrudate is shown in Figure 2. The lack of a gelatinization peak after extrusion indicated complete starch gelatinization in the extrudates The high temperatures during extrusion assured the conditions needed for the starch to gelatinize. The results obtained were in line with previous studies [40,41].

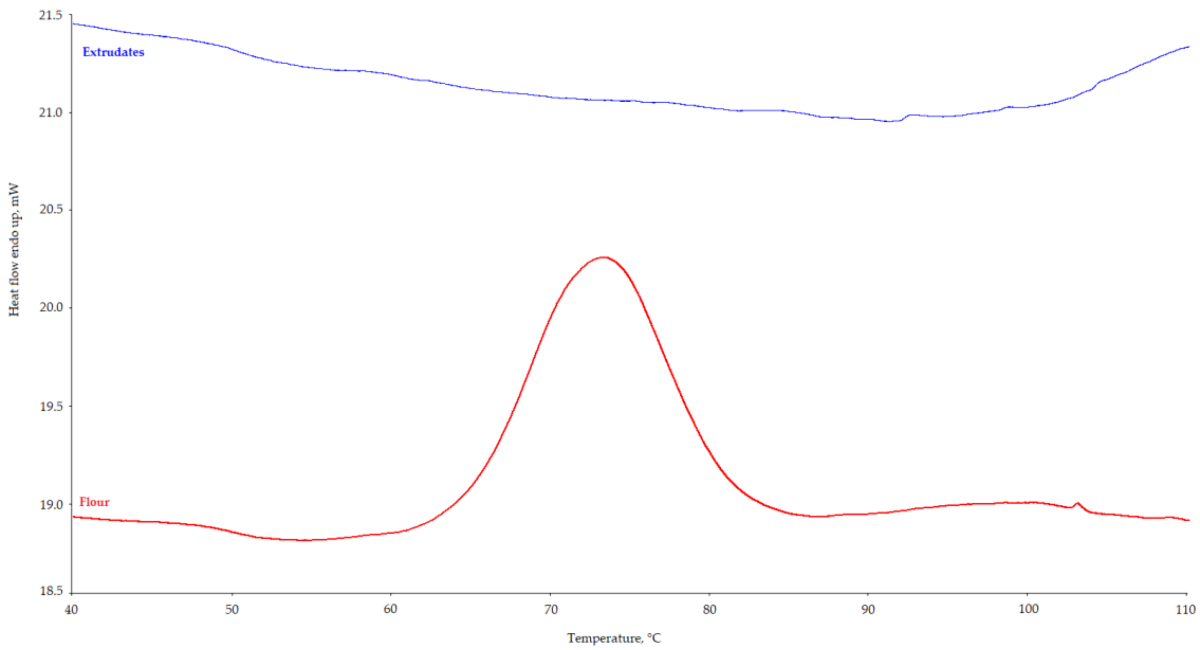

Figure 2. DSC curves for the flour mixture before extrusion (red curve) and extrudate sample (blue curve).

3.4. Total Polyphenolic Content and Antioxidant Activity of Extrudates

The total polyphenolic content (TPC) and antioxidant activity of the ingredients are presented in Figure 3. The TPC in decreasing order was basil > rosehip > turmeric > beetroot > broccoli > paprika > chili > lucerne > pea. A highly positive correlation was found between the TPC and antioxidant activity of the powders (r = 0.9721; $p < 0.05$). In previous research, there was high variability in the TPC and antioxidant activity reported for the type of powders analyzed. The differences that appeared were explained not only by the type of variety/cultivar analyzed [42–45] but also by the extraction solvents used in the analyses [46,47]. Some examples of the TPC include 3.47–17.58 mg GAE/g d.m. for basil [44], 4057.95–6784.55 mg GAE/100 g d.m. for rosehip [45], 496.76–745.76 mg GAE/100 g for turmeric [48], 820.1–1280.56 mg GAE/kg for beetroot [49], 8.22 mg GAE/g d.m. for broccoli [50], 14.67–22.25 mg GAE/g for paprika [51], 24.46–28.18 mg GAE/g for chili [51], 7.68 mg GAE/g for lucerne [52], and 2.38 mg GAE/g [53].

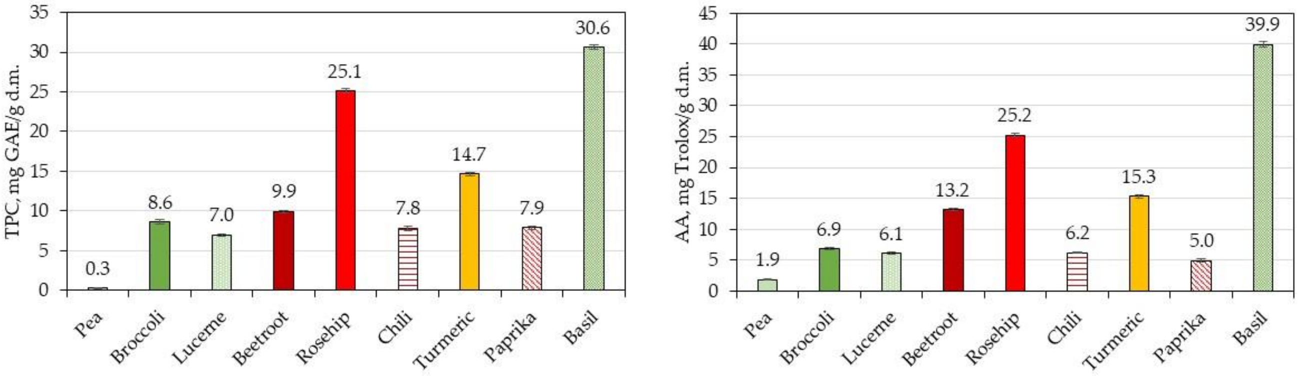

Figure 3. Total polyphenolic content (TPC) and antioxidant activity (AA) of the ingredients.

The TPC and antioxidant capacity of the raw formulations and extrudates are shown in Table 4. As expected to occur, the TPC and antioxidant capacity increased when the corn flour was replaced with the different types of ingredients, which are good sources of bioactive compounds. The lowest value of the TPC was observed for E_control, while the highest value was observed for E_rosehip followed by E_beet, E_basil, and E_broccoli ($p < 0.05$). Among the extrudates with condiment additions, E_basil showed the highest TPC value ($p < 0.05$), whereas no significant differences ($p > 0.05$) were found among E_chili, E_turmeric, and E_paprika, respectively. Additionally, a higher TPC and AA were reported for the rice extrudates with carob and pea additions than for the simple rice extrudates [54] or for the corn extrudates with a broccoli flour addition or an olive paste addition [20]. The turmeric addition in the cereal-based extrudates had a high content of phenolic compounds and a high antioxidant activity, proving to be a high-quality additive due to its technological and bioactive properties [55].

Table 4. Total polyphenolic content (TPC) and antioxidant activity (AA) of raw mixtures (before extrusion) and extrudates (after extrusion).

Sample	TPC, mg GAE/100 g d.m.		AA, mg Trolox/100 g d.m.	
	Before Extrusion	**After Extrusion**	**Before Extrusion**	**After Extrusion**
E_control	95.23 ± 0.6 $^{e\ A}$	55.78 ± 2.14 $^{e\ B}$	90.33 ± 1.53 $^{f\ A}$	53.26 ± 1.64 $^{g\ B}$
E_pea	98.62 ± 0.65 $^{de\ A}$	72.97 ± 1.63 $^{d\ B}$	91.16 ± 0.71 $^{f\ A}$	59.44 ± 1.63 $^{f\ B}$
E_broccoli	122.96 ± 2.28 $^{c\ A}$	94.73 ± 3.76 $^{c\ B}$	109.77 ± 1.13 $^{d\ A}$	83.42 ± 0.86 $^{d\ B}$
E_lucerne	100.77 ± 2.37 $^{de\ A}$	81.17 ± 2.15 $^{d\ B}$	105.67 ± 3.06 $^{de\ A}$	83.48 ± 2.41 $^{d\ B}$
E_beet	213.01 ± 3.42 $^{b\ A}$	172.29 ± 2.67 $^{b\ B}$	254.39 ± 6.58 $^{b\ A}$	250.48 ± 4.25 $^{b\ A}$
E_rosehip	260.30 ± 5.70 $^{a\ B}$	312.02 ± 5.39 $^{a\ A}$	282.59 ± 4.58 $^{a\ B}$	329.20 ± 3.24 $^{a\ A}$
E_chili	98.05 ± 2.36 $^{de\ A}$	80.05 ± 5.34 $^{d\ B}$	97.97 ± 0.50 $^{ef\ A}$	63.68 ± 0.33 $^{f\ B}$
E_turmeric	104.11 ± 2.26 $^{d\ A}$	77.49 ± 2.68 $^{d\ B}$	101.59 ± 1.67 $^{de\ A}$	64.00 ± 1.05 $^{ef\ B}$
E_paprika	99.15 ± 3.42 $^{de\ A}$	74.81 ± 2.09 $^{d\ B}$	97.25 ± 1.74 $^{ef\ A}$	70.02 ± 1.25 $^{e\ B}$
E_basil	117.85 ± 3.48 $^{c\ A}$	104.16 ± 2.69 $^{c\ B}$	142.67 ± 2.08 $^{c\ A}$	104.15 ± 1.52 $^{c\ B}$

Values are means ± standard deviations (n = 3). Different small letters in same column indicate significant differences between mixtures or extrudates ($p < 0.05$). Different capital letters within a row indicate significant changes between the mixtures and the corresponding extrudates ($p < 0.05$).

Compared to the raw formulations, all the extrudates, except E_rosehip, showed a decrease in the TPC ranging from 11 to 41%, with the smallest loss (11%) occurring for E_basil and the highest loss (41%) occurring for E_control, respectively. The same observation was recorded for the antioxidant capacity of the extrudates, with a decrease between 2 and 41%. As in the case of the TPC, the greatest decrease in the antioxidant capacity after extrusion was recorded for the control extrudate. It was underlined that extrusion has a negative effect on different phenolic compounds [31]. Various studies underlined the reduction effect of extrusion on the total polyphenol content and antioxidant properties of extrudates compared to the pre-extrusion flours [5,22], which occurred because of the modification of the molecular structure of the phenolic compounds at temperatures above 80 °C. However, due to the extrusion process, the extraction of phenolic compounds could be enhanced by disintegrating cell wall matrices and breaking up complex polyphenols, with high-molecular-weight phenolic compounds breaking up into low-molecular-weight phenolic compounds with scavenging activity [17]. Other processes that were related to the increase in the antioxidant activity after extrusion referred to the interaction of the phenolic compounds with proteins under heat treatment and the formation of Maillard reaction products [56]. Thus, there are studies that, by applying the optimal extrusion conditions, have reported increases in the total polyphenol content and antioxidant activity after extrusion: extrudates from corn flour and beans [57,58], extrudates from corn flour and lucerne [33], ready-to-eat snacks with cauliflower byproducts [59], extrudates from corn flour with mango byproducts [8], and rice-flour-based extrudates with goji berries [9]. These studies were in line with the results obtained for the extrudate with a rosehip addition, where the TPC and antioxidant capacity increased by 20% and 16%, respectively, when comparing the extrudate with the unextruded sample.

Arribas et al. [60] stated that the use of low temperatures (<140 °C) and a relatively low humidity (<14%) during extrusion can lead to higher phenolic contents and can enhance the antioxidant activity. Additionally, Nayak et al. [56] showed that extrusion retained the antioxidant capacities of the raw formulations in purple-potato- and yellow-pea-based extrudates either in their natural forms or in their degraded products with radical scavenging activity.

A high positive correlation was noted between the TPC and AA of the extrudates (r = 0.9674; $p < 0.05$). This suggests that the antioxidant activity of the extrudates was mainly due to their phenolic content, and this is in agreement with other research that reported a high correlation in broccoli extrudates [20] and rosehip extrudates [1].

3.5. In Vitro Protein Digestibility of Extrudates

The in vitro protein digestibility of the extrudates is given in Figure 4. Among all the extrudates, the highest level of protein digestibility ($p < 0.05$) was in the extrudate with a pea addition followed by broccoli and lucerne ($p > 0.05$). This is in line with previous research where, for products containing legumes, a higher protein digestibility was reported: brown-rice-flour-based extrudates containing 15–45% bean flour [61] and wheat-based extrudates fortified with various legume flours (lentils, chickpeas, and peas) at 5–15% levels of addition [21]. The increase in the protein digestibility of the extrudates with legume additions was related to the denaturation of proteins due to heat and shearing during extrusion and to the degradation of protein complexes [5,21].

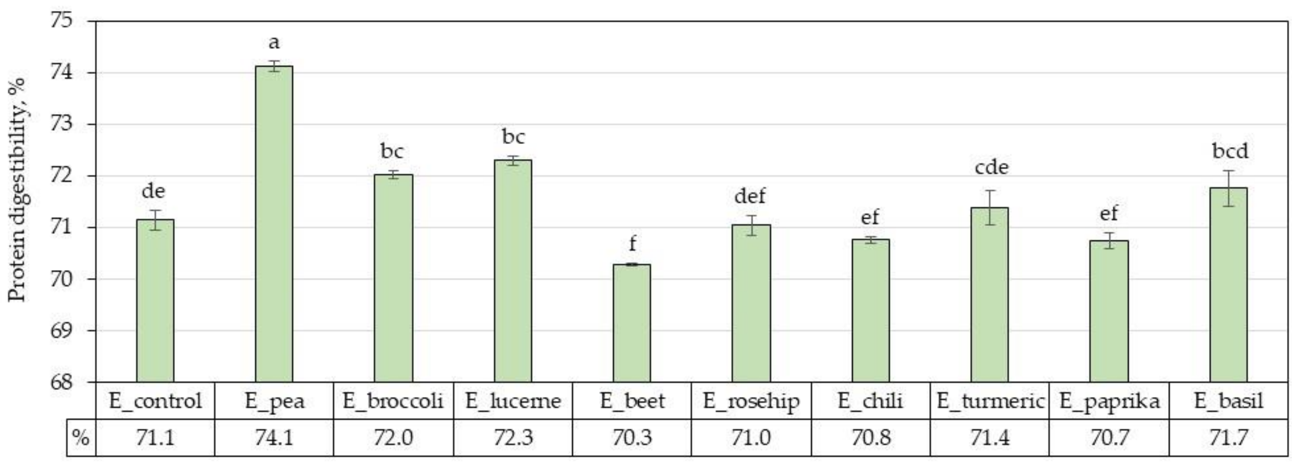

Figure 4. In vitro digestibility of the extrudates. Each bar represents mean values ± standard deviations (n = 3). Different letters indicate significant differences between samples ($p < 0.05$).

No significant differences were found between E_control and E_rosehip, E_chili, E_turmeric, E_paprika, and E_basil ($p > 0.05$). On the other side, the addition of beetroot led to a significant decrease in the protein digestibility of the extrudate ($p < 0.05$). This could be explained by the presence of antinutritional factors, such oxalates, which are present in a high amount in beets [62]. The presence of antinutritional compounds (such as phytates, lectins, protease inhibitors, and oxalates) in different plants sources can impact protein digestibility [63]. However, it was shown that different types of processing can improve protein digestibility, decreasing the antinutrient content and increasing the solubility of proteins [21,63,64].

3.6. Predicted Glycemic Index of the Extrudates

The processing parameters of the extrusion technique (screw configuration, speed, temperature, moisture, and die diameter) affect the starch conformation and physicochemical structure and, therefore, the glycemic index of the extruded products [3,65].

Early research showed the lower digestibility of legume starches compared to cereal starches due to the presence of a higher level of resistant starch and slow digestible starch in legumes [66]. Patil et al. [67] showed that corn-based extrudates with the addition of various amount of peas (5%, 10%, and 15%) showed a lower glycemic response (i.e., a lower release of reducing sugars). Additionally, in bread formulation, the addition of 15% broccoli flour reduced the glycemic index of bread from 100 to 70 [50]. In the present study, the incorporation of peas, broccoli, and lucerne in the corn-based extrudates had a decreasing effect on the glycemic index compared to the control extrudate, but no clear significant differences were observed between the samples ($p > 0.05$) (Figure 5). This is probably because of the lower addition level (2% for peas and 5% for broccoli and lucerne) used for the extrusion of the corn flour.

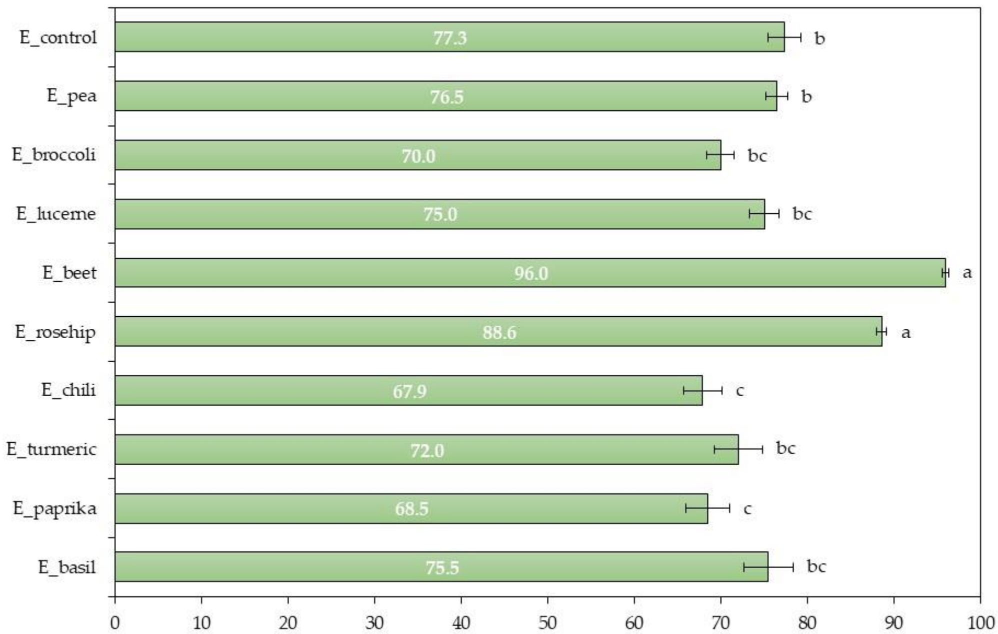

Figure 5. In vitro glycemic index of extrudate samples. Bars represent standard errors of means (n = 3), and means with different letters are significantly different ($p < 0.05$).

Some studies showed that the glycemic index of the extrudates decreased significantly through the use of ingredients with a high fiber content, such as oat fiber [68]; fenugreek polysaccharides [69]; or a mixture of oat, fenugreek, and green peas [70]. However, in this study, E_rosehip and E_beet, the extrudates with the highest fiber content, showed the highest glycemic index. This could be due to a possible degradation of the polysaccharides of rosehip and beetroot during extrusion. Ferreira et al. [71] stated that, during the extrusion of corn-based breakfast cereals with an inulin addition, the degradation of inulin may have taken place, modifying its degree of polymerization and thus avoiding the reduction in the glycemic index. The extruded corn samples with condiment additions were not significantly different ($p > 0.05$) with respect to their glycemic index, showing, however, a lower value than the control extrudate. Uğur et al. [72] demonstrated that some dietary polyphenols present in different types of herbs, including turmeric, reduced starch digestion, hindering α-amylase and α-glucosidase and thereby decreasing the glycemic index of breads.

3.7. Discrimination of the Extrudates with the Electronic Nose

The discrimination map of the overall volatile composition of the corn extrudates achieved by means of the PCA analysis is shown in Figure 6. In the PCA plot, the total contribution rate of the two components was 99.3% (PC1 accounted for 98.44%, and PC2 accounted for 0.86%), and a discrimination index of 86, calculated through the PCA analysis, was obtained. Higher values for the discrimination index in the PCA plot lead to better discrimination [73]. Thus, the volatile profiles of the corn extrudates were different, with a clear separation of the samples. It was noticed that the extrudates with condiment additions were grouped in the upper part of the PCA plot. E_control and E_pea were placed in the bottom-left part of the PCA graph, being opposite to E_broccoli and E_lucerne (the bottom-right part).

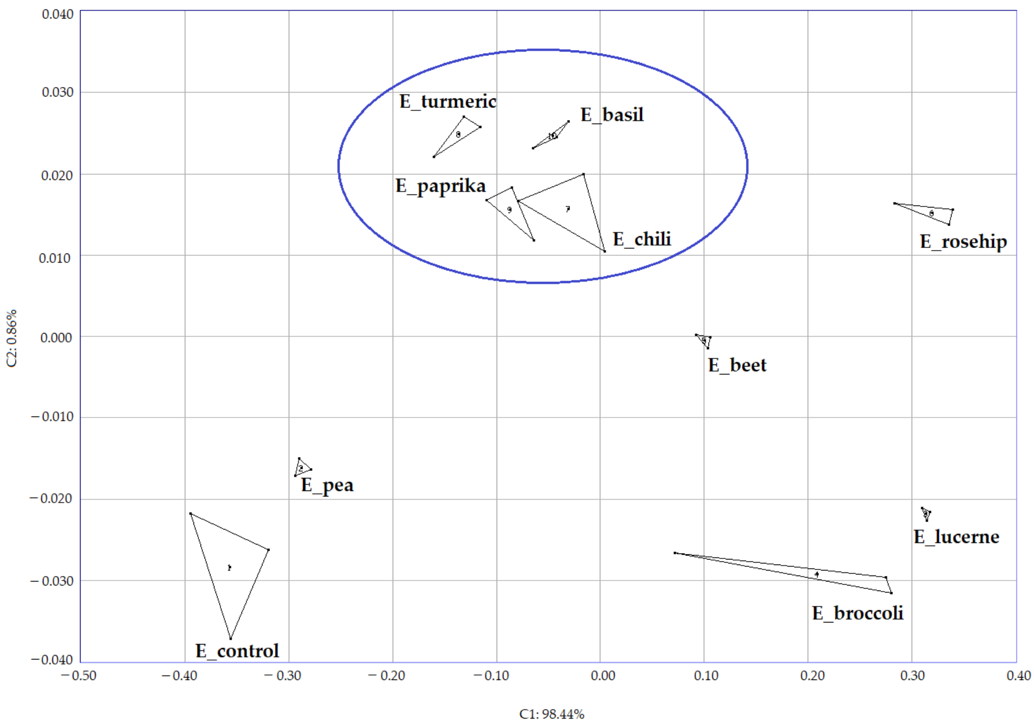

Figure 6. Discrimination of the extrudates based on PCA analysis of overall volatile composition.

During the extrusion process, different volatile compounds are formed through the Maillard reaction and lipid degradation. Igual et al. [33] found that hexanal, limonene, β-myrcene, and eucalyptol were the main volatile compounds in corn extrudates containing lucerne. In the present study, besides the Maillard reaction, the difference in the volatile compounds in the corn extrudates is also ascribed to the different types of ingredients used in the formulations.

3.8. Sensory Evaluation of the Extrudates

The overall acceptability scores of the extrudates were found to vary from 2.5 to 7.5 (Figure 7). E_control showed a higher preference (7.5), but this was not significantly different ($p > 0.05$) from the extrudates E_pea (7.1), E_paprika (7.0), and E_beet (6.9). The addition of lucerne, turmeric, and basil decreased the overall acceptability of the extrudates to an average score of five. The lowest scores (2.5) were for the extrudates with broccoli and rosehip, respectively.

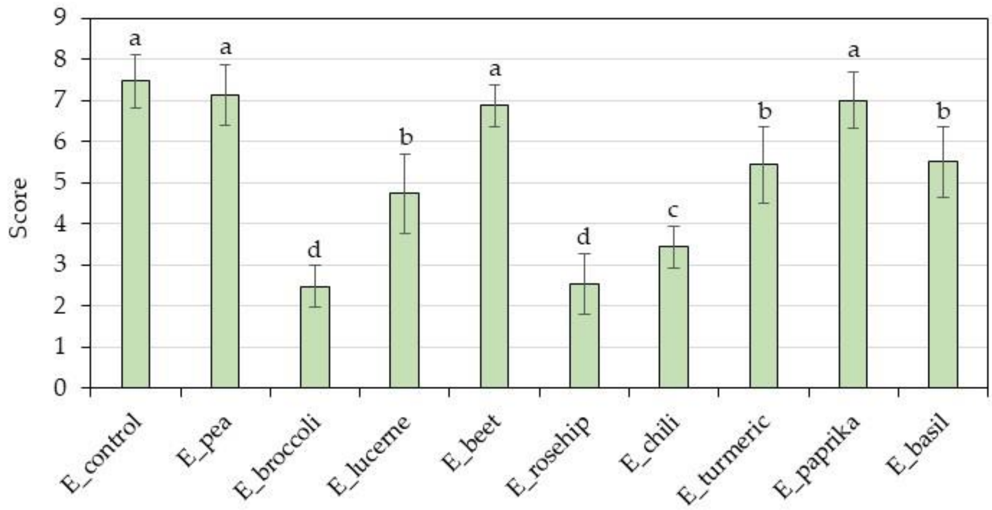

Figure 7. Overall acceptability of the extrudates. Each bar represents mean values ± standard deviations (n = 30). Different letters indicate significant differences between samples ($p < 0.05$).

The sensory scores for appearance were similar for E_control, E_pea, E_beet, E_chili, E_turmeric, and E_paprika (7.07–7.60; $p > 0.05$) followed by E_rosehip and E_basil (5.47–5.93; $p > 0.05$), E_lucerne (3.93; $p < 0.05$), and broccoli (2.33; $p < 0.05$). The highest scores for hardness were obtained for the control and the extrudates with peas, beetroot, turmeric, and paprika (7.07–7.73; $p > 0.05$). The extrudate E_broccoli had the lowest score (2.6; $p < 0.05$) when compared to the others. Sensory hardness was negatively correlated with the hardness values measured with the texture analyzer instrument (r = −0.7826; $p < 0.05$). Similar results were reported by Altan et al. [74].

Regarding the taste of the extrudates, there were no significant differences ($p > 0.05$) between E_control, E_pea, E_beet, E_turmeric, E_paprika, and E_basil, with scores between 7.1 and 7.4. Lower sensory scores ($p > 0.05$) were observed for the extrudates with chili, lucerne, rosehip, and broccoli (3.2–4.0). High correlations were found between the extrudates' taste and overall acceptability (r = 0.9219; $p < 0.05$), the extrudates' hardness and overall acceptability (r = 0.7280; $p < 0.05$), and the extrudates' appearance and overall acceptability (r = 0.6955; $p < 0.05$). This showed that the taste had a higher contribution to the overall acceptability of the extrudates as it was assessed by the evaluators.

Singh et al. [11] found that beetroot incorporation in corn extrudates led to higher scores for overall acceptability, appearance, mouthfeel, and color compared to the control. Rice extrudates with the addition of different levels of paprika oil extract (1–7%) had good sensory acceptability, with scores above 6.0 [75]. Acceptable corn–broccoli extrudates were obtained at a feed moisture content of 14% (for 4% broccoli flour additions) and 16.5% (for 7% broccoli), respectively [20]. In the present study, a lower moisture content of the mixtures before extrusion (i.e., 12%) was employed, which explains the lower scores for acceptability.

4. Conclusions

The extruded products were prepared from blends of corn flour and different ingredients: legume protein sources (peas, broccoli, and lucerne), plants (beetroot and rosehip), and condiments (chili, turmeric, paprika, and basil), respectively. The highest TPC was found for E_rosehip followed by E_beet, E_basil, and E_broccoli. A decrease in the TPC ranging from 11% (E_basil) to 41% (E_control) was seen in all the extrudates, except E_rosehip, where an increase of 20% was observed, when comparing the extrudates with the unextruded sample. The highest level of protein digestibility was in the corn extrudate with a pea addition followed by broccoli and lucerne, while beetroot led to the opposite impact. The extruded corn samples with condiment additions had a lower glycemic index than the control extrudate. The expansion ratio increased when paprika and chili were added to the corn flour, while a contrary effect was obtained for the corn blends with broccoli, rosehip, lucerne, and peas. The hardest extrudate was that with broccoli supplementation followed by rosehip, lucerne, and peas. The extrudates with condiments had the lowest value of hardness. The beetroot, paprika, turmeric, chili, and pea extrudates were darker with more intense red and yellow colors. This study supports the utilization of different types of ingredients in extruded products, providing not only improved nutritional properties but also a natural color in the final extrudates, which could play an important role in the consumers' point of view as well as in the expansion of the extruded gluten-free market. To conclude, from each category of ingredients considered (i.e., legume proteins, plants, and condiments), the additions of peas, beetroot, and paprika, respectively, in corn extrudate manufacturing are highly recommended.

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