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Nutritious corn extrudates enriched with Andean Lupin and pecan nut: Physicochemical, textural, nutraceutical and sensory properties

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ABSTRACT

The study aimed to produce nutritious and functional gluten-free corn-based extrudates by incorporating whole Andean lupin flour (WLF) and ground pecan nut (GPN). A D-optimal mixture design assessed the effects of WLF, GPN, moisture levels (13%, 15%, and 17%), and screw rotation speeds (324, 360, and 396 rpm) in a co-rotating twin-screw extruder. The research evaluated compositional properties, total phenols (TPC), condensed tannins (TCT), antioxidant capacity, expansion, hydration, mechanical properties, pasting behavior, and sensory attributes. High-performance liquid chromatography (HPLC) was used to analyze phenolic acids, flavonoids, and catechins. WLF enhanced protein, fiber, and ash content, while GPN increased TPC, TCT, and antioxidant capacity. Moisture was identified as the key factor affecting all variables. Quadratic models explained the bioactive compound behaviors, and linear models described other properties, with R^2adjust values between 0.87 and 0.99. Significant correlations were found between protein, ash, fiber, TPC, ABTS, and TCT. The optimized extrudates exhibited a 58% increase in protein, a 32% rise in phenols, and notable improvement in antioxidant capacity. Consumer preference favored extrudates with higher GPN content, while those with higher WLF content were tasteless. Optimal extrudates containing over 3.2 g/100 g GPN showed enhanced profiles of phenolic acids, flavonoids, and catechins.

1. Introduction

Ready-to-eat (RTE) foods have seen a surge in demand due to their convenience and time-saving attributes, making them highly appealing to modern consumers. However, these products are often criticized for their limited nutritional and nutraceutical profiles (Brennan et al., 2013). Expanded snacks or puffed extrudates, a popular category of RTE foods, are typically produced from refined flours derived from grains such as corn, wheat, and rice. These grains are rich in starch but low in dietary fiber and protein. To a much lesser extent, from oats, sorghum, millets, barley, and rye are also used. These cereal grains, of high starch content (>60%), can undergo significant expansion during low moisture

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extrusion cooking process, a technique that not only enhances product texture but also improves its digestibility and shelf life (Collantes et al., 2022; Gomes et al., 2023).

To enhance the nutritional, functional or nutraceutical quality of extruded RTE products, several studies have incorporated protein-rich raw material with significant starch content to maintain extrudate expansion. These include pseudocereals like quinoa, buckwheat and amaranth as well as pulses such as beans, lentils, chickpeas, and faba bean (Altan & Yağci, 2023; Berrios et al., 2022; Brennan et al., 2012). Currently, efforts have been made to incorporate lipid-rich and non-starch raw materials, including non-conventional legumes like peanuts and lupin. Additionally, oilseeds including nuts like chestnuts, cashews, pecans, almonds and coconuts, have also been incorporated (Farhana Meharaj Allai et al., 2022; Muñoz-Llandes et al., 2023; Naseer et al., 2021). Nevertheless, few studies have combined these two types of raw materials in corn-based extrudates in order to improve their nutritional and nutraceutical profile without significant lack of extrudate expansion.

In this context, the Andean lupin (*Lupinus mutabilis*), also known in South America as "tarwi or chocho" in Inca language, is a legume rich in proteins (~48%), lipids (~20%), fiber (~20%) and bioactive compounds such as tocopherols, carotenoids, phenolic compounds and flavonoids, mainly apigenin derivatives such as apigenin-6,8-di-*C*-β-glucopyranoside and apigenin 7-*O*-β-apiofuranosyl-6,8-di-*C*-β-glucopyranoside, and isoflavones such as genistein and daidzein (Brandolini et al., 2022; Czubinski et al., 2021). These natural antioxidants can strengthen the immune system by reducing excess of free radicals or radical oxygen species (ROS), and may help to prevent cardiovascular disease, obesity, metabolic syndrome, menopausal symptoms, neurological disorders and breast cancer (Clemente-Suárez et al., 2023; Cortés Avendaño, 2020). On the other hand, the pecan nut (*Carya illinoinensis*) is an oilseed rich in lipids, whose nutritional contribution lies mainly in the presence of essential fatty acids of the omega-3 group, including α-linolenic acid (ALA, C18:3n-3), eicosapentaenoic acid (EPA, C20:5n-3) and docosahexaenoic acid (DHA, C22:6n-3) (Siebeneichler et al., 2023; Tanwar et al., 2021; Villasante et al., 2019). It also contains bioactive compounds such as tannins, flavonoids, including (+)-catechin, and phenolic acids such as caffeic acid, protocatechuic acid and gallic acid, which are known to have antioxidant and anti-inflammatory properties (Cheung et al., 2023).

Extrusion cooking offers an alternative for developing enriched healthy products with beneficial components. This versatile technology combines heat, shear, and pressure in short processing times, making it widely used in the grain food processing industry. It integrates multiple unit operations to thermo-mechanically transform cereals, pseudocereals, pulses, oilseeds, roots, and tubers into expanded products such as "ready-to-eat snacks" and "techno-functional flours" by adjusting process parameters such as temperature profile, moisture, screw speed and feed rate (Collantes et al., 2022; Ek & Ganjyal, 2020). In addition, extrusion cooking enhances nutrient bioavailability, creates novel textures, and incorporates functional ingredients. It also allows the use of non-conventional materials, such as pulses, ancient grains, and plant-based proteins, by improving the nutritional profile of products. These innovations meet growing consumer demand for health-conscious, high-protein, fiber-rich, and sustainable options (Asif et al., 2023). However, this study has limitations, including a narrow focus on specific ingredients, possible effects on bioactive retention and a lack of in-depth sensory data from consumers. Future research should investigate a broader range of ingredients, to optimize the process, and to assess the health effects of phytochemicals through *vivo* assays. Additionally, by integrating nutrigenomics it could reveal how these ingredients may influence the gene expression and health outcomes at molecular level. Therefore, the objectives of this research were to (1) evaluate the effects of adding Andean lupin and pecan nut at varying feed moistures and screw speeds to produce functional extrudates, (2) model the compositional, antioxidant, physical, mechanical, and paste properties, (3) characterize the enriched extrudates sensorially, and (4) quantify the phenolic acids, flavonoids, and catechins in the optimal extrudates.

2. Material and methods

2.1. Raw materials

The commercial corn grits were acquired from Corina S.A.C. and the whole lupin (*Lupinus mutabilis* var. "Andenes 90") flour was acquired from Tarwicorp S.A.C., both in the city of Lima (Peru). The pecan nut was obtained from the local market in the city of Ica (Peru), which was ground in a processor CL 50 ultra (Robot coupe, Montceau-en-Bourgogne, France) to reduce the particle size that was sieved on an opening size of 1000 μm to obtain granulated ground pecan.

2.2. Flour moisture regulation

The different mixtures based on corn grits (CG), whole lupin flour (WLF) and ground pecan nut (GPN) were pre-conditioned according to the method described by Collantes et al. (2022). Previously, the flours were mixed in a planetary mixer model BH20 (Nova, Lima, Peru) by 15 min to make the total mixture uniform, then 2 g of sample in triplicated were taken and placed on a thermobalance model MX-50X (A&D Weighing, Kawasaki, Japan) to determine the initial moisture content of the mixture. Then, the amount of water to be added to reach 13, 15, 17% moisture content was calculated according to the following equation (1):

$$W = \frac{(M_f - M_i)\ x\ TM}{100 - M_f} \quad (1)$$

Where W is the volume of water added (mL), M_f is the final moisture content of the mixture (%), M_i is the initial moisture content of the mixture (%) and TM is the total weight of the mixture (g).

2.3. Extrusion process

The extrusion process was carried out in a co-rotating twin screw extruder EB6 - 60X (Galix Tech, Huancayo, Peru) with two temperature control zones (100 °C and 150 °C, from the feed to the output), barrel length of 85 cm, length/diameter (L/D) ratio of 13.02, and equipped with an output round die of 6.34 mm diameter running at feeder rate of 66 kg/h. The flour blends at varied moisture content (13, 15 and 17%) were fed into the extruder feed zone at screw speeds of 324, 360 and 396 rpm.

2.4. Chemical composition

The chemical composition of the raw materials was determined according to AOAC (2000), moisture content (method 925.10), total fat content (method 983.23), total protein content (method 2000.11, using a protein factor conversion of 5.75), ash content (method 923.03), crude fiber content was determined by AOCS method (Ba 6a-05), and carbohydrate content was determined by difference. All results were expressed on a dry matter (DM) basis. The theoretical calculation of the composition of the extrudates was based on the raw materials. .

2.5. Total phenolic compounds (TPC)

The extraction and quantification of TPC was performed on raw materials and extruded samples, according to the Folin-Ciocalteu method modified by Chávez et al. (2017). For extraction, 2.5 g of ground sample were placed in a 25 mL amber flask and filled with 70% acetone (v/v). The mixture was vortexed for 1 min, left to stand for 30 min, and filtered using quantitative paper. One milliliter of the extract was transferred to a 10 mL volumetric flask and diluted with distilled

water. This procedure was repeated in triplicate. Next, 10% Folin-Ciocalteu (v/v) and 7.5% sodium carbonate (Na_2CO_3) (w/v) solutions were prepared with distilled water. For the TPC reaction, 250 μL of the sample extract and 1.25 mL of 10% Folin-Ciocalteu reagent were mixed, homogenized, and reacted for 2 min at room temperature. Then, 1 mL of 7.5% sodium carbonate solution was added. The test tubes were incubated at 50 °C for 15 min, followed by 30 s in ice bath to stabilize the reaction. The blank consisted of 250 μL of 7% acetone, 1.25 mL of 10% Folin-Ciocalteu, and 1 mL of sodium carbonate solution, following the same procedure. The absorbance readings were taken at a wavelength of 760 nm using a spectrophotometer Genesys 150 (Thermo Fisher Scientific, Waltham, MA, USA), and the TPC quantification was determined using a gallic acid (GA) standard curve (2.5, 3.5, 5, 7, 8, 10, and 12 mg/L). The calibration curve equation was y = 0.0624x - 0.039 with an R^2 of 0.998. The results were expressed as mg GAE/100 g DM.

2.6. Determination of antioxidant capacity by $ABTS^{\bullet+}$ and $DPPH^{\bullet}$

a. Extract obtention

The extraction was carried out in two steps following the methodology of Saura-Calixto, Serrano, and Goñi (2007). The first with 50% methanol and the second with 70% acetone. For the first extraction, 1 g of sample was weighed into a 15 mL centrifuge tube, and 2 mL of 50% methanol was added. The mixture was vortexed for 1 min and shaken intermittently every 20 min for 60 min at room temperature, protected from light. The sample was centrifuged at 3000 rpm for 16 min, and the supernatant was transferred to a 5 mL beaker. In the second extraction, 2 mL of 70% acetone was added to the residue from the first extraction, and the procedure was repeated. The supernatants from both steps were combined and made up to 5 mL with distilled water.

b. $ABTS^{\bullet+}$ assay

The radical scavenging capacity by $ABTS^{\bullet+}$ ion (2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) was determined using the modified method described by Chávez et al. (2017). The method is based on antiradical capacity evaluation through the decolorization of the free radical. To prepare solution A, 0.1920 g of $ABTS^{\bullet+}$ was dissolved with 50 mL distilled water in a 10 mL amber flask. For solution B, 0.3780 g potassium persulphate ($K_2S_2O_8$) was dissolved in distilled water in a 10 mL amber flask. Then, 10 mL of solution A and 0.176 mL of solution B were combined in a 25 mL amber flask, homogenized, and stirred for 30 min. The radical was stored at room temperature for 16 h. Next, a diluted $ABTS^{\bullet+}$ solution in 95% ethanol was prepared by mixing 1.5 mL of the $ABTS^{\bullet+}$ radical with 100 mL ethanol and stirring for 20 min. The absorbance was checked in order to ensure that it was between a wavelength of 0.680 and 0.720 nm using spectrophotometer Genesys 150 (Thermo Fisher Scientific, Waltham, MA, USA); if needed, it was adjusted with ethanol or the $ABTS^{\bullet+}$ radical.

To determine antioxidant capacity, 90 μL of the sample extract were mixed with 3 mL of the diluted $ABTS^{\bullet+}$ solution and allowed to stand for 4 min before measuring absorbance at a wavelength of 734 nm. The blank consisted of 90 μL ethanol and 3 mL of the diluted $ABTS^{\bullet+}$ solution. Antioxidant capacity was quantified using a calibration curve with 1, 8, 20, 30, and 40 μM Trolox concentrations. Results were expressed as μM Trolox equivalent/100 g DM, using the following calibration curve y = 0.0294x - 0.0268 with R^2 = 0.999.

c. *$DPPH^{\bullet}$ assay*

The radical scavenging capacity by $DPPH^{\bullet}$ (2,2-Diphenyl-1-picrylhydrazyl) ion was determined using the modified method described by Chávez et al. (2017). This method assesses antiradical capacity based on the decolorization of free radicals. To prepare the $DPPH^{\bullet}$ solution, 0.0030 g of $DPPH^{\bullet}$ was dissolved in methanol in a 100 mL amber flask to achieve 60 μM and stirred for 15 min. The absorbance of the $DPPH^{\bullet}$ solution was verified at a wavelength of 517 nm using spectrophotometer Genesys 150 (Thermo Fisher Scientific, Waltham, MA, USA). The reaction was carried out by mixing 100 μL of the sample extract with 2.9 mL of $DPPH^{\bullet}$ solution, homogenized, and allowed to react for 30 min. For the blank, distilled water replaced the sample. Antioxidant capacity was expressed as μM Trolox equivalent/100 g DM, by using a calibration Trolox curve (5, 60, 150, 350, 400, and 500 μM), based on the equation y = 0.000020042x - 0.0204 with R^2 = 0.9861.

2.7. Total condensed tannins (TCT)

TCT quantification was performed using the modified vanillin methodology used by Vargas-Solórzano et al. (2014). To obtain the extract, 1 g of sample was mixed with 5 mL of a 10% methanol-hydrochloric acid solution (v/v) in an amber flask. The mixture was stored in a light-protected container at 4 °C for 16 h. The extract was centrifuged at 4000 rpm for 16 min and filtered through rapid quantitative filter paper. For the TCT reaction, 1 mL of the sample extract was combined with 5 mL of 4% vanillin (w/v) in 10% methanol-hydrochloric acid solution (v/v), and incubated for 20 min. Absorbance was measured at 500 nm using a spectrophotometer Genesys 150 (Thermo Fisher Scientific, Waltham, MA, USA). The blank consisted of 5 mL of the vanillin solution incubated for 20 min before absorbance readings. Condensed tannins were expressed as mg catechin equivalent/100 g DM, by using a catechin calibration curve (0.01–0.7 mg/mL), with the equation y = 1.3036x - 0.0551 (R^2 = 0.9851).

2.8. Expansion properties

Sectional (SEI), longitudinal (LEI) and volumetric expansion indexes (VEI) were determined according to the method described by Alvarez-Martinez et al. (1988). The bulk density (BD) was calculated as the ratio of the extrudate weight to its volume, which was determined using the small seed displacement method described by Pardhi et al. (2019). In this method, the volume of three pre-weighed extrudates was measured.

2.9. Hydration properties

Water absorption (WAI) and water solubility (WSI) indexes were determined according to the modified method described by Vargas-Solórzano et al. (2014). Ten grams sample knife-milled that passed through a 106 μm sieve aperture was analyzed. Then, 0.5 g of the sieved sample was weighed into a 15 mL falcon tube, to which 10 mL of distilled water was added. The mixture was homogenized in a vortex until fully dissolved, followed by intermittent vortexing for 1 min with 4 min rest intervals until reaching 30 min. The samples were then centrifuged at 9000 rpm for 30 min. The supernatant was separated and evaporated in a vessel, followed by dehydration in an oven UN30 (Memmert, Schwabach, Germany) at 105 °C for 4 h until constant weight was achieved. The remaining solid was weighed to determine the WAI according to equation (2), while the dehydrated supernatant was weighed to calculate the WSI using equation (3).

$$WAI = \frac{g\ water\ absorbed\ of\ sediment}{g\ dry\ sample} \quad (2)$$

$$WSI = \frac{g\ of\ dissolved\ solids\ in\ supernatant}{g\ dry\ sample} \times 100 \quad (3)$$

2.10. Texture instrumental analysis

The extrudate texture was determined according to Collantes et al. (2022), using the puncture method described by Bouvier et al. (1997) and employing a texture analyzer TA-XT Plus (Stable Micro Systems, Surrey, UK) equipped with a 30 kg load cell and a 2 mm wide stainless

steel cylindrical probe. The extrudates were drilled to a depth of 50% of their diameter with a compression force of 0.2 N and at a speed of 1 mm/s per specimen. The readings were generated by Exponent software (Stable Micro Systems, Surrey, UK) version 4.0.13.0, using the following parameters to determine the extrudate textural properties, as follows.

- Spatial frequency of structural ruptures (Nsr, mm^{-1}).

$$Nsr = N_0/d \quad (4)$$

Where N_0 is the total number of peaks and d is the puncture distance (mm).

- Average force of specific structural ruptures (Fsr, N).

$$Fsr = \sum \frac{\Delta F}{N_0} \quad (5)$$

Where ΔF are the individual force drops for each peak.

- Average puncture force (F, N).

$$F = \frac{A}{d} \quad (6)$$

Where A is the integral under the force versus deformation curve (N·mm).

- Crispness work (Wc, N·mm).

$$Wc = \left(\frac{F}{Nsr}\right) \quad (7)$$

2.11. Pasting profile

Paste viscosity profiles were measured using a rapid viscosity analyzer (Newport Scientific Pty Ltd., Warriewood, Australia) following the methodology of Collantes et al. (2022). A 3.5 g sample of ground extrudates was conditioned to 14% moisture (wet basis) and mixed with 25 mL of distilled water. The mixture was stirred at 160 rpm at 25 °C for 2 min, heated to 95 °C for 3 min, and then cooled to 25 °C for 5 min, totaling 20 min. Paste properties were determined, including cold viscosity at 25 °C (CV, cP), peak viscosity (PV, cP), trough viscosity (TV, cP), breakdown (BDV = PV - TV, cP), final viscosity (FV, cP), and setback viscosity (SBV = FV - TV, cP).

2.12. Sensory analysis

a Consumers

Panelists were recruited from the Professional School of Agro-industrial Engineering at the Universidad Privada San Juan Bautista. A total of 100 consumers participated, of which 60% were female and 40% male, with an average age of 24 ± 6 years. Their participation was voluntary, and the study was conducted with informed consent approved by the Institutional Committee of Ethics in Research (CIEI) of the Universidad Privada San Juan Bautista (No. 1202-2024-CIEI-UPSJB).

b. Check all that apply (CATA) and Overall liking

One hundred regular snack consumers participated and gave informed consent to conduct the sensory evaluation (UNE, 2021). For the CATA and general acceptability test, the methodology of Chávez et al. (2021) was followed with some adaptations in the descriptors chosen by the panelists.

2.13. Quantification of phenolic compounds by HPLC-DAD for optimal extrudates

a Phenolic acids and flavonoids analysis

Quantification of phenolic acids (PA) and flavonoids of the best extrudates was performed by HPLC-DAD following the method reported by Barriga-Sánchez et al. (2024). All results were expressed on a dry matter (DM) basis.

b Catechins analysis

The catechins analysis was performed following the methodology of Wang et al. (2003), employing a Chromaster high-performance liquid chromatography system with diode array detector (Hitachi High-Technologies Corporation, Tokyo, Japan) was used.

2.14. Statistical analysis

The D-optimal design was used, with two components of the mixture, whole lupin flour (WLF, Z_1, g/100 g) and ground pecan nut (WPN, Z_2, g/100 g) and two process variables such as feed moisture (X_1, %) and screw speed (SS-rpm, X_2) generating 12 treatments with 2 replicates (Table 1). The effects of the independent variables were evaluated by a linear model as follows:

$$Y = \beta_1 Z_1 + \beta_2 Z_2 + \beta_{12} Z_1 Z_2 + \theta_1 X_1 + \theta_2 X_2 + \theta_{12} X_1 X_2 + \theta_{11} X_1^2 + \theta_{22} X_2^2 + \varepsilon$$

Where:

Y is the response variable to be fitting.

Z_1 and Z_2 are the mixture components WLF and WPN respectively.

X_1 and X_2 represent the processed variables moisture and screw speed

β1, β2, θ1, θ2, represent the linear effect of each variable

β12, is the quadratic effect for mixture components

θ12, is the interaction effect for mixture components

θ11, θ22, are the quadratic effects for moisture and screw speed.

One-way ANOVA, followed by LSD Fisher and Scott Knott multiple range tests, was used to identify the differences between samples, while Dunnett's test compared treatments with the control at a 95% significance level. Additionally, multivariate analysis included principal component analysis (PCA) and a heatmap were employed to assess variable intensity, along with hierarchical clustering of principal components (HCPC). Finally, Pearson's correlation test was conducted to determine positive or negative associations between variables, using correlation strength categories proposed by Teles et al. (2019). The free software R version 3.2.4 (R Foundation for Statistical Computing, Vienna, Austria) was used for all data analyses.

3. Results and discussions

3.1. Composition and antioxidant properties

Corn grits (CG) had higher carbohydrate content, primarily starch, and significant antioxidant capacity from the presence of carotenoids than Andean lupin and pecan. In contrast, Andean lupin (WLF) showed high protein (52.37 g/100 g), lipids (24.17 g/100 g), and crude fiber (18.69 g/100 g) content, serving as a low-calorie ingredient with double the minerals than pecan nut (GPN) and CG. GPN exhibited the highest lipid content (70.74 g/100 g), notable protein level ($p < 0.05$), and strong antioxidant capacities linked to the presence of tocopherols, tannins, flavonoids, and phenolic acids (Wojdyło et al., 2022).

All enriched extrudates exhibited higher protein increase, ranging from 36.8 to 59.5 g/100 g compared to the control ($p < 0.05$). The highest protein values, 12.92, 11.95, 11.87, and 11.81 g/100 g, were observed in the treatments T2, T5, T6, and T12 ($p < 0.05$), respectively.

Table 1
Composition and total bioactives of raw materials and extrudates (dry matter basis) enriched with added Andean lupin and pecan nut produced at different feed moisture and screw speeds.

Components	WLF (Z_1, g/100 g)	GPN (Z_2, g/100 g)	FM (X_1, %)	SS (X_2, rpm)	Chemical composition (g/100 g)						Total bioactives and antioxidant properties			
					Ash	Protein	Lipids	Crude Fibre	Carbohydrates	Dry. material	TPC	ABTS	DPPH	TCT
Raw materials														
Corn grits	–	–	–	–	1.02 ± 0.02^{a}	7.65 ± 0.10^{a}	4.13 ± 0.05^{a}	0.59 ± 0.10^{a}	86.61 ± 0.06^{c}	86.41 ± 0.06^{a}	20.41 ± 0.75^{a}	7.90 ± 0.13^{b}	3001.99 ± 71.91^{b}	0.002 ± 0.00^{a}
Andean lupin	–	–	–	–	2.29 ± 0.03^{c}	52.37 ± 0.09^{c}	24.17 ± 0.06^{b}	18.69 ± 0.32^{c}	2.47 ± 0.43^{a}	92.54 ± 0.06^{b}	18.04 ± 1.11^{a}	2.91 ± 0.04^{a}	1235.81 ± 31.11^{a}	0.050 ± 0.00^{b}
Pecan nut	–	–	–	–	1.29 ± 0.02^{b}	9.90 ± 0.04^{b}	70.74 ± 0.34^{c}	3.07 ± 0.03^{b}	14.99 ± 0.35^{b}	95.74 ± 0.01^{c}	228.06 ± 7.42^{b}	310.43 ± 8.06^{c}	154795.00 ± 875.52^{c}	6.057 ± 0.00^{c}
Extrudates	Experimental design													
Control	0.00	0.00	15	324	1.02 ± 0.01	7.65 ± 0.10	4.13 ± 0.04	0.59 ± 0.10	86.61 ± 0.06	86.4 ± 0.06	13.24 ± 0.36	5.43 ± 0.23	3156.60 ± 151.30	ND
T1	6.1	3.9	17	324	1.11 ± 0.03$^{a,\alpha}$	10.47 ± 0.11$^{f,\alpha}$	7.95 ± 0.05$^{a,\alpha}$	1.79 ± 0.07$^{c,\alpha}$	78.68 ± 0.04$^{a,\alpha}$	87.14 ± 0.03$^{a,\alpha}$	14.00 ± 0.11^{d}	7.17 ± 0.21$^{a,\alpha}$	3670.00 ± 59.90$^{a,\alpha}$	0.002 ± 0.00^{f}
T2	10.0	0.0	15	324	1.15 ± 0.02$^{a,\alpha}$	12.12 ± 0.14$^{a,\alpha}$	6.14 ± 0.04$^{h,\alpha}$	2.40 ± 0.06$^{a,\alpha}$	78.20 ± 0.01$^{g,\alpha}$	87.02 ± 0.06$^{a,\alpha}$	11.70 ± 0.45$^{e,\alpha}$	5.01 ± 0.28$^{f,\alpha}$	3170.30 ± 118.70^{c}	ND
T3	7.9	2.1	15	324	1.12 ± 0.03$^{a,\alpha}$	11.23 ± 0.10$^{d,\alpha}$	7.11 ± 0.04$^{d,\alpha}$	2.07 ± 0.06$^{b,\alpha}$	78.46 ± 0.02$^{c,\alpha}$	87.09 ± 0.05$^{a,\alpha}$	13.64 ± 0.19^{d}	6.33 ± 0.21$^{d,\alpha}$	3171.60 ± 84.80^{c}	0.002 ± 0.00^{f}
T4	6.1	3.9	15	324	1.11 ± 0.01 $^{a,\alpha}$	10.47 ± 0.12$^{f,\alpha}$	7.95 ± 0.05$^{a,\alpha}$	1.79 ± 0.07$^{c,\alpha}$	78.68 ± 0.04$^{a,\alpha}$	87.14 ± 0.06$^{a,\alpha}$	14.15 ± 0.27^{d}	7.41 ± 0.20$^{a,\alpha}$	3478.8 ± 53.30$^{b,\alpha}$	0.019 ± 0.00^{c}
T5	9.6	0.4	17	396	1.14 ± 0.04$^{a,\alpha}$	11.95 ± 0.13$^{a,\alpha}$	6.32 ± 0.04$^{g,\alpha}$	2.34 ± 0.06$^{a,\alpha}$	78.25 ± 0.01$^{f,\alpha}$	87.03 ± 0.07$^{a,\alpha}$	12.28 ± 0.74^{e}	6.10 ± 0.22$^{d,\alpha}$	3147.30 ± 65.20^{c}	0.005 ± 0.00^{f}
T6	9.4	0.6	15	396	1.14 ± 0.02$^{a,\alpha}$	11.87 ± 0.14$^{a,\alpha}$	6.42 ± 0.04$^{g,\alpha}$	2.31 ± 0.06$^{a,\alpha}$	78.27 ± 0.01$^{f,\alpha}$	87.04 ± 0.05$^{a,\alpha}$	11.62 ± 0.71$^{e,\alpha}$	5.50 ± 0.18^{e}	2740.70 ± 150.10$^{d,\alpha}$	0.004 ± 0.00^{f}
T7	8.3	1.7	15	396	1.13 ± 0.01$^{a,\alpha}$	11.40 ± 0.10$^{c,\alpha}$	6.93 ± 0.04$^{e,\alpha}$	2.14 ± 0.06$^{a,\alpha}$	78.41 ± 0.02$^{d,\alpha}$	87.07 ± 0.06$^{a,\alpha}$	12.42 ± 0.53^{e}	6.52 ± 0.18$^{c,\alpha}$	3246.00 ± 132.30^{c}	0.005 ± 0.00^{f}
T8	7.6	2.4	15	396	1.12 ± 0.03$^{a,\alpha}$	11.10 ± 0.12$^{d,\alpha}$	7.25 ± 0.04$^{c,\alpha}$	2.03 ± 0.06$^{b,\alpha}$	78.50 ± 0.03$^{c,\alpha}$	87.10 ± 0.07$^{a,\alpha}$	14.28 ± 0.15^{d}	6.74 ± 0.18$^{b,\alpha}$	3486.90 ± 57.10$^{b,\alpha}$	0.005 ± 0.00^{f}
T9	9.1	0.9	13	360	1.14 ± 0.04$^{a,\alpha}$	11.74 ± 0.14$^{b,\alpha}$	6.55 ± 0.04$^{f,\alpha}$	2.26 ± 0.06$^{a,\alpha}$	78.31 ± 0.01$^{e,\alpha}$	87.05 ± 0.06$^{a,\alpha}$	15.32 ± 0.83$^{c,\alpha}$	6.90 ± 0.11$^{b,\alpha}$	2565.60 ± 88.90$^{e,\alpha}$	0.012 ± 0.00^{d}
T10	9.0	1.0	13	360	1.14 ± 0.03$^{a,\alpha}$	11.70 ± 0.12$^{b,\alpha}$	6.60 ± 0.04$^{f,\alpha}$	2.24 ± 0.06$^{a,\alpha}$	78.32 ± 0.01$^{e,\alpha}$	87.05 ± 0.04$^{a,\alpha}$	14.12 ± 0.83^{d}	6.27 ± 0.09$^{d,\alpha}$	2782.80 ± 119.10$^{d,\alpha}$	0.001 ± 0.00^{e}
T11	6.8	3.2	13	360	1.11 ± 0.01$^{a,\alpha}$	10.76 ± 0.11$^{e,\alpha}$	7.63 ± 0.05$^{b,\alpha}$	1.90 ± 0.07$^{c,\alpha}$	78.60 ± 0.03$^{b,\alpha}$	87.12 ± 0.03$^{a,\alpha}$	17.53 ± 0.78$^{a,\alpha}$	7.32 ± 0.06$^{a,\alpha}$	3514.10 ± 16.40$^{b,\alpha}$	0.025 ± 0.00^{b}
T12	9.5	0.5	17	324	1.14 ± 0.03$^{a,\alpha}$	11.91 ± 0.10$^{a,\alpha}$	6.37 ± 0.04$^{g,\alpha}$	2.32 ± 0.06$^{a,\alpha}$	78.26 ± 0.01$^{f,\alpha}$	87.03 ± 0.06$^{a,\alpha}$	11.55 ± 0.11$^{e,\alpha}$	5.67 ± 0.15^{e}	2548.70 ± 83.50$^{e,\alpha}$	0.003 ± 0.00^{f}
T13 (R)	7.6	2.4	15	396	1.12 ± 0.01$^{a,\alpha}$	11.10 ± 0.14$^{d,\alpha}$	7.25 ± 0.04$^{c,\alpha}$	2.03 ± 0.06$^{b,\alpha}$	78.50 ± 0.03$^{c,\alpha}$	87.10 ± 0.05$^{a,\alpha}$	13.37 ± 0.46^{d}	6.11 ± 0.18$^{d,\alpha}$	3432.20 ± 55.80$^{b,\alpha}$	0.007 ± 0.00^{e}
T14 (R)	6.8	3.2	13	360	1.11 ± 0.03$^{a,\alpha}$	10.76 ± 0.13$^{e,\alpha}$	7.63 ± 0.05$^{b,\alpha}$	1.90 ± 0.07$^{c,\alpha}$	78.60 ± 0.03$^{b,\alpha}$	87.12 ± 0.04$^{a,\alpha}$	16.46 ± 0.11$^{b,\alpha}$	7.50 ± 0.12$^{a,\alpha}$	3390.60 ± 10.50$^{b,\alpha}$	0.043 ± 0.00^{a}

Results expressed as mean ± standard deviation, n = 10. Control: 100% corn grits, T1-T14: 90% corn grits, R: repetitions, WLF: whole lupin flour, GPN: ground pecan nut, FM: feed moisture, SS: screw speed, TPC: total phenolic compounds (mg gallic acid equivalent/100 g DM), ABTS: 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) was expressed as μmol trolox equivalents/100 g DM, DPPH: 2,2-Diphenyl-1-picrylhydrazyl was expressed as μmol trolox equivalent/100 g DM, TCT: total condensed tannin (mg catequin equivalent/kg DM), ND: not detected, below the limit of detection. Different lower case letters in the same column indicate significant differences between treatments by Scott Knott and the Greek letter (α) indicates significant differences of the treatments with the control according to Dunnett's test ($p < 0.05$).

These increases were attributed to the higher addition of WLF, which ranged from 9.4 to 10 g/100 g in these treatments (Table 1). Such protein contents were similar to the *L. angustifolius*-based extrudates reported by Muñoz-Llandes et al. (2023), although they included 47 g/100 g of germinated lupin, but were superior to the extrudates developed by Adem et al. (2020). It clearly demonstrates the potential of Andean lupin as a dense source of protein. Furthermore, the extrudates showed increases in ash (8–10 g/100 g), lipids (54.9–92.5 g/100 g) and fiber (203–306.7 g/100 g), while carbohydrates decreased by about 10 g/100 g in all samples.

The TPC content of the extrudates ranged from 11.62 to 17.53 mg GAE/100 g (Table 1). The extrudates with GPN greater than 2.1 g/100 g showed significant increases in TPC than the control, having T11 treatment the highest concentration of 17.53 mg GAE/100 g ($p < 0.05$). While extrudates with the highest WLF content and less than 2 g/100 g GPN had significant decrease in TPC. This was due to the washing and parboiling process used to remove alkaloids from the Andean lupin, which in turn reduced total phenolic content. In addition, feed moisture influenced TPC degradation, since at 13% moisture showed the highest retention, while higher moisture levels increased heat transfer, hence TPC degradation (Fig. 1a). This effect of moisture on TPC showed a quadratic behavior with an R^2adjust of 0.99 (TS1), as demonstrated by Bekele et al. (2021).

Furthermore, the TPC in the extrudates were lower than those reported by Allai et al. (2022), who found 587 mg GAE/100 g in optimized whole grain-based extrudates added of 2.5% horse chestnut and under process parameters of moisture/SS/T that were 12%/380 rpm/130 °C, respectively. Such extrudates showed higher TPC retention because they had a mild extrusion process with shorter residence time or cooking time, which caused lower degradation of phenolic compounds. A similar effect was observed for feed moisture on both the degradation of antioxidant capacity by ABTS, and the concentration of TCT (Fig. 1b and c), where linear surface response was obtained with R^2adjust = 0.99 with quadratic components (TS1).

Furthermore, the increase in antioxidant capacity measured by DPPH was observed in the extrudates with GPN additions higher than 2.1 g/100 g (Table 1), hence the proportion of this component had a preponderant influence on this chemoprotective property. In addition, among the process parameters, it was found that the combination of high moisture (17%) and screw speed (396 rpm) (Fig. 1c), led to extrudates with the highest antioxidant capacity by DPPH, as observed in treatment T1 ($p < 0.05$). Also, the response surface generated for the DPPH values had a quadratic behavior with a fit R^2adjust = 0.99 (TS1).

The TCT concentrations in the extrudates were very low (Table 1), as well as those of TPC and ABTS, which were also significantly affected by the high feed moisture (Fig. 1d), with treatments T11 and T14 showing the highest TCT retentions among the samples ($p < 0.05$), as they combined both the highest GPN and the lowest feed moisture (13%). In addition, the behavior of TCT was linear with some quadratic components and had fits of R^2adjust = 0.87 (TS1). Also, the TCT results

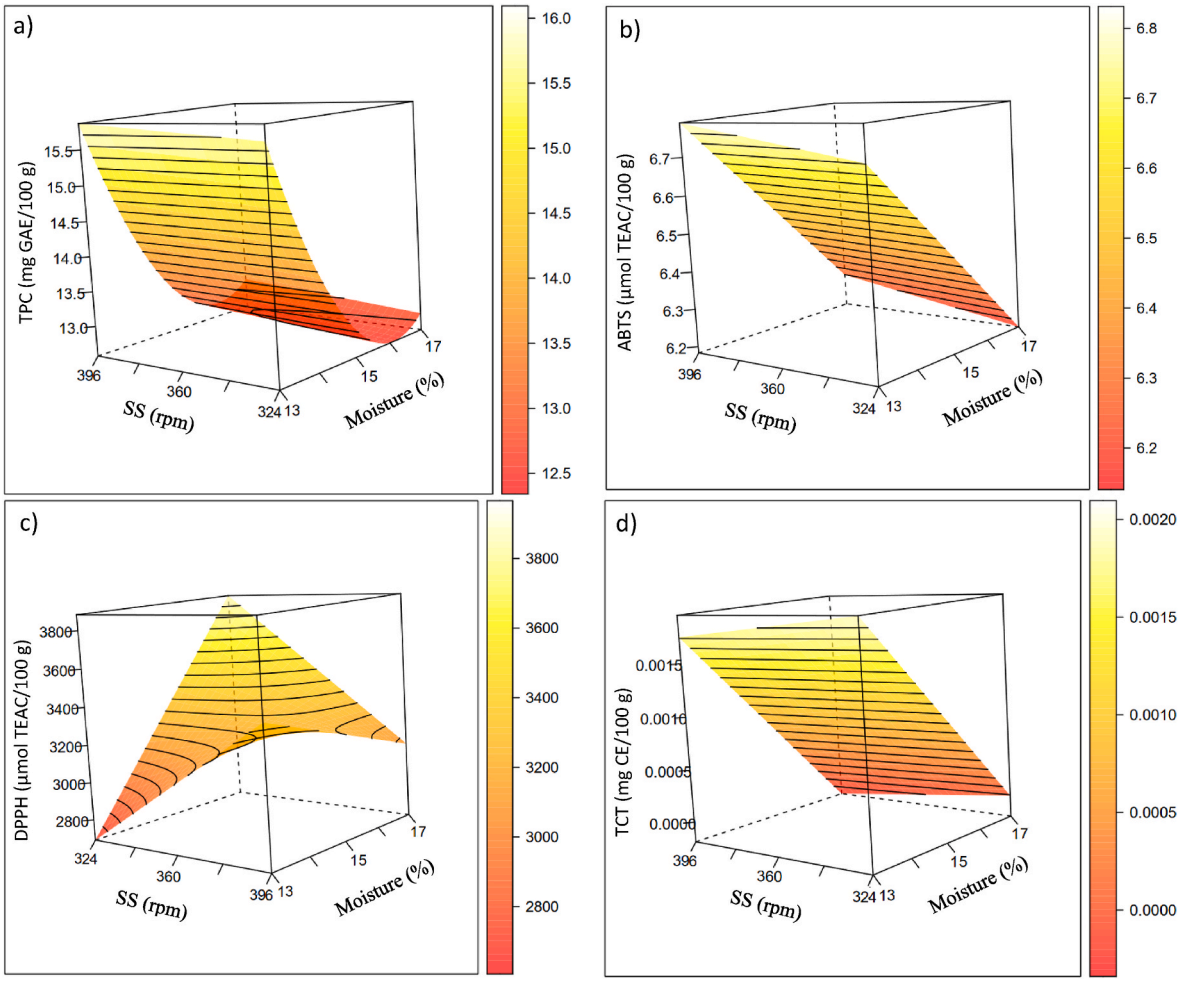

Fig. 1. Response surface of bioactive compounds in extrudates enriched with Andean lupin and pecan nut. a) TPC: total phenol compounds (mg gallic acid equivalent/100 g, GAE: gallic acid equivalent), b) ABTS: 2,2′-Azino-bis(3- ethylbenzothiazoline-6-sulfonic acid) was expressed as µmol trolox equivalent/100 g, DPPH: 2,2-Diphenyl-1- picrylhydrazyl was expressed as µmol trolox equivalent/100 g and d) TCT: total condensed tannin (mg catechin equivalent/kg, CE: catechin equivalent).

obtained for extrudates were lower than those obtained by Tadesse et al. (2019) for sorghum-based extrudates with soybean addition.

3.2. Expansion properties

The sectional expansion index (SEI) is the most important property in the extrudate development. In the enriched prototypes, the SEI ranged from 10.99 to 18.58, being T5, T6 and T13 the treatments with the best expansion, with SEI values of 18.58, 17.99 and 18.54, respectively. These values were statistically similar to the control, which had an SEI of 19.30 ($p > 0.05$) (Table 2). Furthermore, these values were higher than those reported by Choi et al. (2021); Gasparre et al. (2020) who incorporated soy protein and 10% tiger nuts in rice-based extrudates. Also, T5, T6 and T13 were the treatments with the lowest BD between 0.102 and 0.104 g/cm^3 among the samples ($p < 0.05$), those were similar to the optimal groundnut, buckwheat and rice-based extrudate obtained by Li et al. (2019) and were lower than the extrudates obtained by Muñoz-Llandes et al. (2023); Sahu et al. (2022); Sobowale et al. (2021) when they used germinated *Lupinus angustifolius*, a mixture of maize-millet-elephant foot yam-soy protein and whole pearl millet-African nut-corn starch to generate nutritious extrudates.

The LEI values ranged from 3.19 to 6.04 (Table 2). T4 and T10 extrudates showed the highest values of LEI ($p < 0.05$), which were higher than the values reported by Allai et al. (2022); Choi et al. (2020); Silva et al. (2014), when they incorporated horse chestnut, soy protein and carioca bean in extrudates based on whole grains (barley, corn, and wheat), rice and maize, respectively. Regarding VEI which denotes the relationship between the densities of the melt and the extrudate, the

Table 2
Expansion, hydration and texture properties of extrudates enriched with Andean lupin and pecan nut at different feed moisture and screw speeds.

Treatment	Experimental design					Expansion and hydration properties					
	CG (g/100 g)	WLF (Z_1, g/100 g)	GPN (Z_2, g/100 g)	FM (X_1, %)	SS (X_2, rpm)	SEI	BD (g/cm^3)	LEI	VEI	WAI	WSI
Control	100	0	0	15	324	19.3 ± 1.52	0.094 ± 0.005	6.62 ± 0.47	127.47 ± 8.81	5.22 ± 0.15	27.81 ± 1.29
T1	90	6.1	3.9	17	324	16.65 ± 1.23$^{b;\alpha}$	0.114 ± 0.008$^{a;\alpha}$	4.13 ± 0.42$^{f;\alpha}$	68.79 ± 8.39$^{e;\alpha}$	4.94 ± 0.1$^{b;\alpha}$	15.88 ± 0.96$^{e;\alpha}$
T2	90	10	0	15	324	15.37 ± 1.4$^{c;\alpha}$	0.111 ± 0.005$^{a;\alpha}$	4.61 ± 0.24$^{e;\alpha}$	70.61 ± 4.39$^{e;\alpha}$	4.91 ± 0.05$^{b;\alpha}$	13.86 ± 0.16$^{f;\alpha}$
T3	90	7.9	2.1	15	324	14.06 ± 0.6$^{d;\alpha}$	0.119 ± 0.010$^{a;\alpha}$	5.65 ± 0.23$^{b;\alpha}$	79.38 ± 3.5$^{c;\alpha}$	4.91 ± 0.15$^{b;\alpha}$	15.15 ± 0.54$^{e;\alpha}$
T4	90	6.1	3.9	15	324	13.89 ± 0.57$^{d;\alpha}$	0.108 ± 0.009$^{b;\alpha}$	6.03 ± 0.21$^{a;\alpha}$	83.74 ± 2.89$^{c;\alpha}$	5.27 ± 0.1^{a}	17.23 ± 0.19$^{d;\alpha}$
T5	90	9.6	0.4	17	396	18.58 ± 1.73^{a}	0.103 ± 0.00^{b}	4.73 ± 0.65$^{e;\alpha}$	87.29 ± 8.69$^{b;\alpha}$	5.01 ± 0.07^{b}	18.43 ± 0.41$^{c;\alpha}$
T6	90	9.4	0.6	15	396	17.99 ± 1.24^{a}	0.102 ± 0.01^{b}	3.93 ± 0.26$^{f;\alpha}$	70.72 ± 6.65$^{e;\alpha}$	4.64 ± 0.07$^{c;\alpha}$	15.25 ± 0.78$^{e;\alpha}$
T7	90	8.3	1.7	15	396	15.40 ± 1.05$^{c;\alpha}$	0.107 ± 0.008^{b}	5.33 ± 0.39$^{c;\alpha}$	81.86 ± 5.07$^{c;\alpha}$	4.82 ± 0.08$^{c;\alpha}$	16.93 ± 1.15$^{d;\alpha}$
T8	90	7.6	2.4	15	396	16.57 ± 0.94$^{b;\alpha}$	0.117 ± 0.009$^{a;\alpha}$	4.94 ± 0.26$^{d;\alpha}$	81.81 ± 6.68$^{c;\alpha}$	4.79 ± 0.17$^{c;\alpha}$	16.79 ± 0.63$^{d;\alpha}$
T9	90	9.1	0.9	13	360	11.59 ± 0.73$^{e;\alpha}$	0.122 ± 0.014 $^{a;\alpha}$	3.19 ± 0.17$^{g;\alpha}$	36.92 ± 2.34$^{g;\alpha}$	4.91 ± 0.16$^{b;\alpha}$	18.06 ± 1.03$^{c;\alpha}$
T10	90	9	1	13	360	13.46 ± 1.19$^{d;\alpha}$	0.107 ± 0.010^{b}	5.85 ± 0.34$^{a;\alpha}$	78.64 ± 6.8$^{c;\alpha}$	4.74 ± 0.12$^{c;\alpha}$	18.51 ± 0.55$^{c;\alpha}$
T11	90	6.8	3.2	13	360	10.99 ± 0.65$^{e;\alpha}$	0.115 ± 0.011$^{a;\alpha}$	4.25 ± 0.13$^{f;\alpha}$	46.63 ± 2.55$^{f;\alpha}$	4.92 ± 0.03$^{b;\alpha}$	19.56 ± 0.7$^{b;\alpha}$
T12	90	9.5	0.5	17	324	16.90 ± 1.27$^{b;\alpha}$	0.117 ± 0.016$^{a;\alpha}$	5.56 ± 0.39$^{b;\alpha}$	93.63 ± 6.22$^{a;\alpha}$	4.91 ± 0.09$^{b;\alpha}$	17.36 ± 0.68$^{d;\alpha}$
T13 (R)	90	7.6	2.4	15	396	18.55 ± 1.28^{a}	0.104 ± 0.011^{b}	4.1 ± 0.24$^{f;\alpha}$	75.93 ± 4.17$^{d;\alpha}$	4.91 ± 0.05$^{b;\alpha}$	18.13 ± 0.9$^{c;\alpha}$
T14 (R)	90	6.8	3.2	13	360	12.18 ± 0.54$^{e;\alpha}$	0.107 ± 0.010^{b}	5.41 ± 0.18$^{c;\alpha}$	65.88 ± 3.89$^{e;\alpha}$	5.16 ± 0.08^{a}	21.06 ± 0.47$^{a;\alpha}$

Treatment	Experimental design					Texture instrumental properties			
	CG (g/100 g)	WLF (Z_1, g/100 g)	GPN (Z_2, g/100 g)	FM (X_1, %)	SS (X_2, rpm)	Nsr (mm^{-1})	Fsr (N)	F (N)	Wc (N.mm)
Control	100	0	0	15	324	2.02 ± 0.47	0.17 ± 0.03	0.06 ± 0.01	0.03 ± 0.00
T1	90	6.1	3.9	17	324	7.36 ± 1.83 $^{c;\alpha}$	0.89 ± 0.20 $^{a;\alpha}$	1.76 ± 1.26 $^{c;\alpha}$	0.16 ± 0.05 $^{d;\alpha}$
T2	90	10	0	15	324	7.05 ± 1.79 $^{c;\alpha}$	0.66 ± 0.12 $^{c;\alpha}$	1.24 ± 0.47 $^{c;\alpha}$	0.18 ± 0.04 $^{d;\alpha}$
T3	90	7.9	2.1	15	324	8.71 ± 0.72 $^{b;\alpha}$	0.57 ± 0.05 $^{c;\alpha}$	1.38 ± 0.19 $^{c;\alpha}$	0.16 ± 0.02 $^{d;\alpha}$
T4	90	6.1	3.9	15	324	10.18 ± 0.85 $^{a;\alpha}$	0.59 ± 0.05 $^{c;\alpha}$	0.92 ± 0.29 $^{d;\alpha}$	0.18 ± 0.03 $^{d;\alpha}$
T5	90	9.6	0.4	17	396	7.32 ± 1.93 $^{c;\alpha}$	0.75 ± 0.16 $^{b;\alpha}$	0.46 ± 0.17 ^{d}	0.23 ± 0.05 $^{c;\alpha}$
T6	90	9.4	0.6	15	396	8.24 ± 0.77 $^{b;\alpha}$	0.58 ± 0.09 $^{c;\alpha}$	1.06 ± 0.28 $^{c;\alpha}$	0.14 ± 0.02 $^{d;\alpha}$
T7	90	8.3	1.7	15	396	5.57 ± 1.25 $^{d;\alpha}$	0.74 ± 0.12 $^{b;\alpha}$	1.22 ± 0.47 $^{c;\alpha}$	0.15 ± 0.02 $^{d;\alpha}$
T8	90	7.6	2.4	15	396	6.90 ± 0.58 $^{c;\alpha}$	0.51 ± 0.07 $^{c;\alpha}$	1.18 ± 0.16 $^{c;\alpha}$	0.17 ± 0.02 $^{d;\alpha}$
T9	90	9.1	0.9	13	360	10.11 ± 0.39 $^{a;\alpha}$	0.59 ± 0.05 $^{c;\alpha}$	2.13 ± 0.49 $^{b;\alpha}$	0.21 ± 0.04 $^{c;\alpha}$
T10	90	9	1	13	360	9.76 ± 0.68 $^{a;\alpha}$	0.49 ± 0.06 $^{c;\alpha}$	1.40 ± 0.24 $^{c;\alpha}$	0.18 ± 0.034 $^{d;\alpha}$
T11	90	6.8	3.2	13	360	7.81 ± 0.61 $^{c;\alpha}$	0.59 ± 0.06 $^{c;\alpha}$	3.34 ± 0.66 $^{a;\alpha}$	0.41 ± 0.053 $^{a;\alpha}$
T12	90	9.5	0.5	17	324	4.28 ± 0.84 $^{e;\alpha}$	0.70 ± 0.17 $^{b;\alpha}$	1.27 ± 0.41 $^{c;\alpha}$	0.28 ± 0.061 $^{b;\alpha}$
T13 (R)	90	7.6	2.4	15	396	6.00 ± 0.54 $^{d;\alpha}$	0.72 ± 0.12 $^{b;\alpha}$	1.34 ± 0.16 $^{c;\alpha}$	0.21 ± 0.01 $^{c;\alpha}$
T14 (R)	90	6.8	3.2	13	360	7.74 ± 0.40 $^{c;\alpha}$	0.58 ± 0.03 $^{c;\alpha}$	2.13 ± 0.27 $^{b;\alpha}$	0.26 ± 0.02 $^{b;\alpha}$

Results represent the mean ± standard deviation (n = 10). Control: 100% corn grits, R: repetitions, CG: corn grits, WLF: whole lupin flour, GPN: ground pecan nut, FM: feed moisture, SS: screw speed, SEI: sectional expanded index, BD: Bulk density, LEI: longitudinal expanded index, VEI: volumetric expanded index, WAI: water absorption index, WSI: water solubility index, Nsr: Spatial frequency of structural ruptures, Fsr: Average force of specific structural ruptures, F: Average puncture force, WC: Crispness work. Different lower case letters in the same column indicate significant differences between treatments by Scott Knott and the Greek letter (α) indicates significant differences of the treatments with the control according to Dunnett's test ($p < 0.05$).

values ranged from 36.92 to 93.63 for the experimental samples, being treatment T12 (93.63) the one with the highest VEI among all the obtained prototypes ($p < 0.05$), followed by treatment T5 (87.29) and also both treatments had higher VEI in comparison to the corn extrudates with soybean meal addition obtained by Sharifi et al. (2021). The response surfaces of all expansion properties (SEI, BD, LEI and VEI) had a linear behavior (Fig. 2a–d) with R^2adjust fits between 0.96 to 0.99 (TS2).

3.3. Hydration properties

WAI was higher in T5, T6, and T14 with values of 5.01, 4.64 and 4.91, respectively, however T5 showed non-significant reduction against the control ($p > 0.05$), but treatments T6 and T14 which had good expansion showed significant reductions in WAI ($p < 0.05$), indicating that the combined inclusion of WLF and GPN produced less starch disruption. On the other hand, WAI results were lower than those reported by Allai et al. (2023) for whole grain-based extrudates with added Indian Horse Chestnut, suggesting that our prototypes may have lower starch digestibility due to lower fragmentation of their granular structure, which is insoluble in water and resistant to hydrolysis by amylases. Also, these values were slightly higher than the WAI values reported by Muñoz-Llandes et al. (2023) in optimized extrudates composed of lupin germinated with corn starch, probably due to the high screw speed (396 rpm), which caused a severe disruption of the supramolecular starch structure, increasing the hydrophilic groups and enhancing water absorption (Xu et al., 2023). The WAI response surface showed a linear behavior (Fig. 2e) with an R^2adjust of 0.99 (TS2). The parameter that significantly influenced the WAI was the screw speed (SS), as higher SS reduced the cooking time in the extruder, leading to less starch fragmentation.

The values of the water solubility index (WSI) in the extrudates ranged from 12.99 to 21.06, which were significantly lower than the control ($p < 0.05$). The T5, T6 and T13 treatments with the best expansion showed WSI values of 18.43, 15.25 and 18.13, respectively, being these values higher compared to the extrudates obtained by Awol et al. (2024); Muñoz-Llandes et al. (2023) who incorporated lupin germinated with corn starch and teff with soybean. Also, as demonstrated in Fig. 2f, the WSI showed quadratic behavior, with an R^2 adjust fit of 0.99. It was observed that feed moisture exerted the most significant influence on WSI, while screw speed had a minor effect on this property associated with starch hydrolysis.

3.4. Texture analysis

Nsr indicates the number of peaks, which results from the breaking of the internal wall cells per unit distance travelled by the sensor during the puncture. For enriched extrudates ranged from 4.28 to 10.18 mm^{-1} (Table 2), which were higher than the control that had 2.02 mm^{-1} ($p < 0.05$). This parameter in the treatments with the best expansions was 7.32, 8.24 and 6.00 mm^{-1} for T5, T6 and T13, respectively. Among them, T13 had a lower number of internal peaks or bubbles per millimeter compared to T5 and T6 (Fig. 3). This was mainly due to the protein-fiber coeffect conferred by high amounts of WLF, which

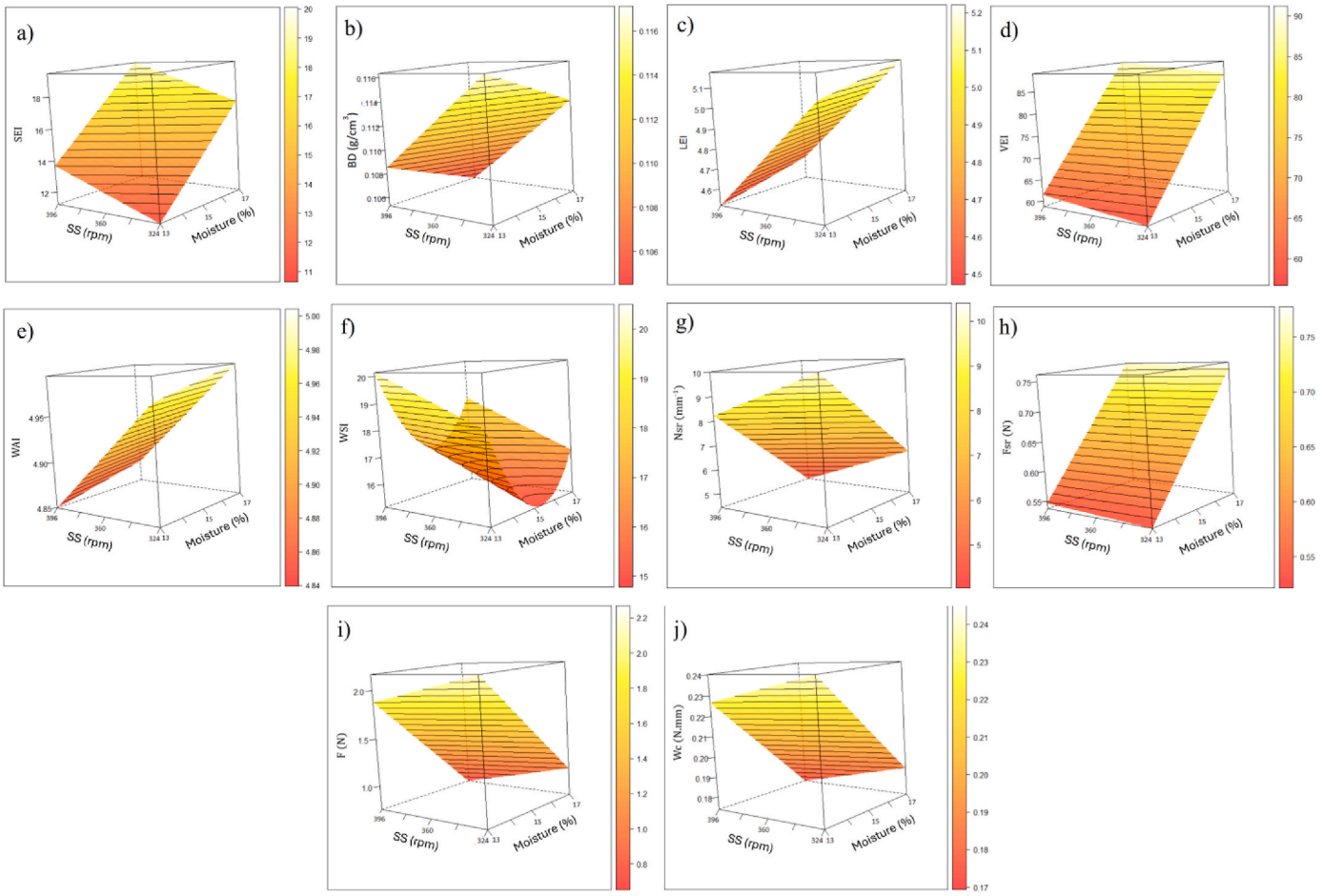

Fig. 2. Response surface of expansion indexes, hydration and texture properties of enriched extrudates. a) SEI: Sectional expansion index, b) BD: bulk density, c) LEI: Longitudinal expansion index, d) VEI: Volumetric expansion index, e) WAI: Water absorption index, f) WSI: Water solubility index, g) Nsr: Spatial frequency of structural ruptures, h) Fsr: Average force of specific structural ruptures, i) F: Average puncture force and j) Wc: Crispness work.

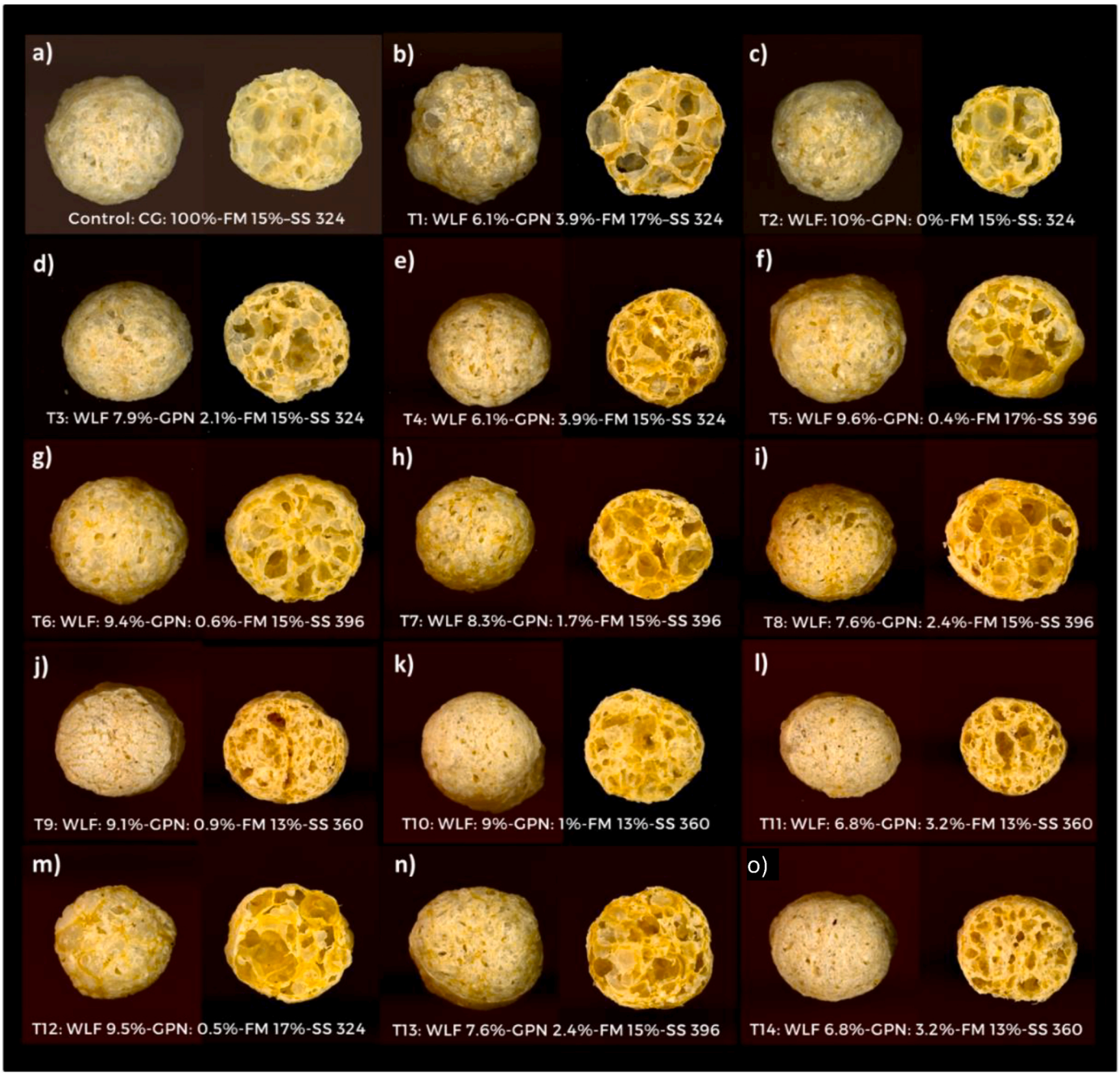

Fig. 3. Images of enriched extrudates with Andean lupin and pecan nut produced at different feed moisture and screw speeds. (a) 100% grit control and (b–o) extrudates enriched with whole lupin flour (WLF) and ground pecan nut (GPN).

generated higher viscosity and surface tension in the bubbles formed due to the coagulation of the proteins during the material melting during the extrusion process.

The Fsr, which measures the structural strength or brittleness of the extrudate, ranged from 0.497 to 0.887 N (Table 2). T6, which had the best expansion, showed the lowest Fsr ($p < 0.05$). This was probably due to the fact that the higher protein content reduced the free water in the system through protein-water interactions, and, together with the higher shear (396 rpm), increased starch depolymerization, both factors contributing to a more fragile extrudate structure (Devi et al., 2013). This moisture effect coincided with García-Segovia et al. (2020), where direct proportional relationships were found between increases in moisture content and higher extrudate hardness.

F, which denotes hardness or puncture resistance, in treatments T5, T6 and T13 with the best expansion, showed values of 0.457, 1.063 and 1.343 N, respectively. However, T5 stood out as having the lowest F value and being statistically similar to the control ($p > 0.05$), despite containing the highest amounts of protein. Such values obtained from T5 despite having 9.6% WLF agreed with Devi et al. (2013), who produced an extrudate based on sorghum, corn (germ-free) and soybean (defatted) flours combined with whey protein isolate, which when incorporating higher protein levels, the puncture force decreased. Wc is the crispness scale and is directly related to the resistance and hardness of the extrudate. The enriched extrudates ranged from 0.144 to 0.276 N mm, all of them being higher than the control ($p < 0.05$), which had 0.03 N mm. Also, T6 had the lowest Wc (0.144 N mm) among the extrudates with the best expansion and at the same time, such results obtained were higher than those reported by Devi et al. (2013).

On the other hand, all the response surfaces of the texture parameters presented linear behaviours with R^{2a}djust fits between 0.87 and 0.98 (Fig. 2g–j and TS2). In Nsr, F and Wc, the simultaneous interaction of lower feed moisture and screw speed produced higher number of bubbles (Fig. 3), thus generating more expanded extrudates with lower hardness (Fig. 2g–i and j), while the opposite behavior occurred when increasing both process parameters. While, the Fsr parameter was only influenced by the feed moisture, which as the feed moisture increased concomitantly led to increases in this parameter (Fig. 2h).

3.5. Paste properties

The paste profiles of all the fortified extrudates were lower than those of the control (Fig. 4a). CV indicates viscosity at room temperature (25 °C), which usually is very low when analyzing native starch granules, in contrast to extrusion sheared starch fragments that are able to interact with water molecules, then increasing the paste viscosity. This parameter was significantly lower in all treatments when compared to the control ($p < 0.05$) (TS3), which suggests that the extrudates were

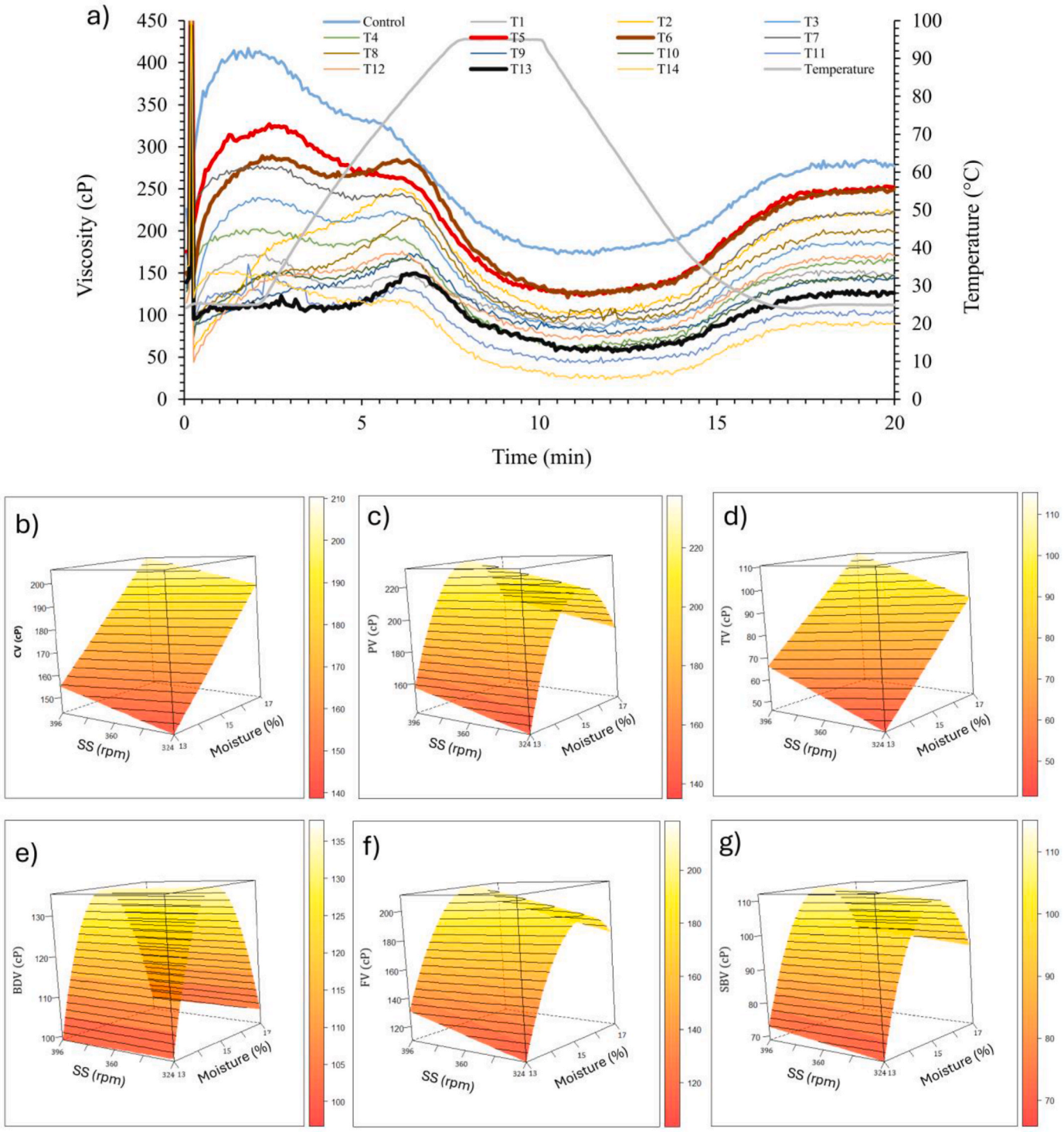

Fig. 4. Pasting profile of enriched extrudates with addition Andean lupin and pecan nut (a) and its response surface of paste properties. b) CV: Cold viscosity, c) PV: Peak viscosity, d) TV: Through viscosity, e) BDV: Breakdown viscosity, f) FV: Final viscosity and g) SBV: Setback viscosity.

low sheared during extrusion due to the presence of higher content of protein and lipids from the lupin and pecan. These CV values were lower than those obtained by Nascimento et al. (2012) for corn-based extrudates with the addition of sesame oil cake. Although the T13 treatment had the best expansion (SEI), it showed the lowest CV values, evidencing a low starch modification after the extrusion cooking process, possibly due to the lipid contribution of the GPN, as lipid acts as lubricant reducing total molecular weight in the extruder. This factor affected starch polymer fragmentation, resulting in low digestibility extrudates, as demonstrated by dos Santos et al. (2024).

PV in extrudates shows the the remaining presence of starch structure integrity seen by their swelling capacity during the RVA heating cycle. Such values in the enriched extrudates ranged from 120 to 295 cP, which were lower than the control at 344 cP ($p < 0.05$). However, the PV value of the control was much higher than enriched samples, however it may not represent the real PV value, given the high cold viscosity that overcame PV reading of the control. For this reason, the PVs of the enriched samples were lower. However, the PVs of the prototypes are more pronounced than the control (Fig. 4a), indicating the presence of fragments of residual intact starch that were able to swell, thus leading to an increase of viscosity (Koa et al., 2017). T5 and T6 showed the highest PV among all the enriched extrudates ($p < 0.05$), which may be attributed to the starch encapsulation by the presence of high protein content in WLF associated with the shorter residence time, as these treatments were carried out at the highest screw speed (396 rpm).

Regarding TV and BDV, which indicate starch disruption after maximum hydration of all starch granules, these parameters were lower in all enriched extrudates when compared to the control ($p < 0.05$), suggesting a reduced degree of starch disruption. Similarly, FV and SBV that are related to starch retrogradation in the enriched samples, they were lower than the control ($p < 0.05$), suggesting that the starch granules may have undergone low depolymerization during extrusion, possibly resulting in minimal changes in amylose content and reduced short-term retrogradation (Comettant-Rabanal et al., 2023). In addition, the reduced TV, BDV, FV and SBV values could be due to the reduction of starch content as a result of replacement by proteins and lipids present in Andean lupin and pecan nut, thus reducing the molecular weight by acting as a lubricant, hence reducing the thermal and shear effects during extrusion (Basto et al., 2016).

The response surfaces of the paste properties had linear and quadratic behavior (Fig. 4b–g). It was observed that feed moisture had a significant effect on CV and TV increases (Fig. 4b and d), and both showed a linear behavior with R^2adjust fits of 0.95 (TS2), respectively. While moisture in PV, BDV, FV and SBV caused quadratic behavior (Fig. 4c–e, f and g) with R^2adjust fits between 0.97 to 0.98 and all of them reached their maximum value with the combination of intermediate moisture (15%) with higher screw speed (396 rpm).

3.6. Sensory analysis

The two dimensions account for a total of 78% of the overall data variability (FS1a), revealing the formation of three distinct consumer groups. The first group consisted of the control sample and T12, positioned in the positive quadrant of both dimensions. The second group was represented by sample T1, located in the negative quadrant of both dimensions. The third group included samples T2, T3, T4, T5, T6, T7, T8, T9, T10, and T11, which were situated between the positive and negative quadrants of the first and second dimensions, respectively. Regarding the sensory characteristics, the first group was described as bitter, greasy, and strong yellow. The second group was characterized as tasteless, while the fourth group exhibited attributes such as sandy, nutty aroma, fibrous, corn aroma, light flavor, light yellow, porous, rugous, crumby, and sticking to teeth.

The penalty graph concerning product acceptability is displayed in FS1b. It shows attributes such as sweet, soft, nutty aroma, strong yellow, salty, and moist enhanced and increased product acceptability. Conversely, attributes like tasteless, dry, hardness, bitter, and greasy reduced snack acceptability. Therefore, it is essential to consider which attributes improved acceptability to achieve a percentage greater than 70% for consumer purchase intent. FS1c presents the acceptability results of the evaluated treatments as reported by consumers. The results indicate that sample T11 had the highest acceptability, showing slightly superior values when compared to the other samples, although it is not significantly different from the control, T4, T6, T7, T9, T10, and T11. In contrast, the sample with the lowest acceptability was T12.

3.7. Phenolic compounds in optimal extrudates enriched with Andean lupin and pecan nut

Extrudates T11 and T12 were chosen for their excellent TPC content, high antioxidant capacity and higher sensory acceptability. In particular, T12 was selected for its similar sensory attributes to the control (FS1a). T11 was the treatment with the best phenolic acid, flavonoid and catechin profile compared to the control (FS2). This treatment presented higher concentrations of caffeic, gallic and ferulic acids ($p < 0.05$) and showed retention of protocatechuic acid, along with slight non-significant increases in syringic acid (Table 3). The presence of these phenolic acids in the enriched extrudates is evidence of the nutraceutical and chemoprotective potential of the prototypes, especially when 3.2% pecan nuts are added. These aromatic secondary metabolites, due to their hydroxyl groups, scavenge free radicals and prevent cell damage associated with oxidative stress, showing well-known anti-inflammatory, cardioprotective, neuroprotective, antimutagenic, antidiabetic, hepatoprotective and antimicrobial properties, as well as anti-proliferative, antiangiogenic and antineoplastic effects, among others (Cadena-Iñiguez et al., 2024; Rashmi & Negi, 2020).

In addition, there were significant increases in flavonoids such as rutin and all catechins ($p < 0.05$). The findings was due to the phytochemicals in Andean lupin and mainly in pecan nut, which, under low moisture (13%) and screw rotation (324 rpm), led to a mild extrusion process that may allowed the retention of phenolic compounds with higher thermal resistance, as they are bound to the pericarp membranes (Blandino et al., 2022; Blandino et al., 2023; Šárka et al., 2021).

However, total degradation in luteolin was observed in both T11 and T12. A similar detrimental effect of the extrusion process on flavonoids was also observed in expanded sorghum-based extrudates (Cardoso et al., 2015), which can be explained by the high sensitivity of these compounds, particularly the π-conjugated bonds and hydroxyl groups. These components make flavonoids vulnerable to heat, as exposure to high temperatures and shear forces can induce the breakdown of conjugated bonds and modification of the functional groups, thus reducing their stability and antioxidant activity (Hirth et al., 2015).

3.8. Multivariate, heatmap and correlation analysis

PC1 and PC2 explained 72.7% of the total variance among a total of 26 variables representing the compositional, physicochemical, textural and paste characteristics of the enriched extrudates. In the upper left quadrant were T5 and T6, which were characterized by the best expansion (Fig. 5a), as can be seen in the heatmap graph by the higher red color intensity (Fig. 5b). They also had the highest paste properties such as CV, which is associated with the degree of starch modification, as well as the highest PV, which indicated the presence of fragments of intact starch with the ability to swell.

In the Pearson correlogram, very strong positive correlations were found between protein with ash and fiber (Fig. 5c), as well as ash with fiber with a correlation coefficient of $0.99 > r \leq 1.00$, showing that the nutritional contribution of these three components occurs simultaneously with the addition of whole Andean lupin and pecan nuts in the corn-based extrudates. Furthermore, good and very high negative correlations were found between carbohydrates and ashes, protein, fat, and fiber, with a correlation coefficient of $-0.92 < r \leq -0.71$. This indicates

Table 3
Phenolic acids, flavonoids and catechins of optimal extrudates enriched with Andean lupin and pecan nut.

Phenolic compounds	λ_{det} (nm)	Retention time (min)	Control	T11	T12
Phenolic acids (mg/kg DM)					
Caffeic acid	280	18.19	0.19 ± 0.01^{a}	0.43 ± 0.01^{c}	0.28 ± 0.01^{b}
Gallic acid		5.12	2.13 ± 0.11^{b}	3.45 ± 0.08^{c}	0.93 ± 0.05^{a}
Sinapic acid		27.92	0.88 ± 0.05	ND	ND
Syringic acid		19.24	0.44 ± 0.01^{b}	0.49 ± 0.01^{b}	0.14 ± 0.01^{a}
Ferulic acid		26.64	4.06 ± 0.0^{b}	4.66 ± 0.01^{c}	2.24 ± 0.01^{a}
3,4-dihydroxybenzoic (protocatechuic) acid		9.16	ND	0.42 ± 0.15	ND
Flavonoids (mg/kg DM)					
Luteolin	280	41.78	3.64 ± 1.74	ND	ND
Rutin		31.96	3.07 ± 0.0^{a}	5.85 ± 0.04^{c}	3.27 ± 0.0^{b}
Phenolic aldehyde (mg/kg DM)					
Vanillin	280	20.81	2.49 ± 0.0^{c}	2.38 ± 0.01^{b}	1.24 ± 0.01^{a}
Catechins (mg/kg DM)					
(+)-Catechin	280	7.94	2.80 ± 0.08^{b}	3.14 ± 0.13^{b}	0.96 ± 0.06^{a}
(−)-Epicatechin		12.38	1.76 ± 0.04^{b}	1.95 ± 0.04^{c}	1.51 ± 0.01^{a}
(−)-Epicatechin-3-gallate		14.27	5.43 ± 0.01^{b}	6.59 ± 0.11^{c}	4.32 ± 0.01^{a}
(−)-Epigallocatechin-3-gallate		19.15	12.88 ± 0.08^{b}	14.23 ± 0.06^{c}	9.45 ± 0.17^{a}

Results expressed as mean ± standard deviation, n = 2. λ_{det}: detection wavelength, Control: 100% corn grits, WLF: whole lupin flour, GPN: ground pecan nut, FM: feed moisture, SS: screw speed. T11: 6.8% WLF and 3.2% GPN at 13% feed moisture and 360 rpm SS, T12: 9.5% WLF and 0.5% GPN at 17% feed moisture and 324 rpm SS, DM: Dry matter basis, ND: not detected, below the limit of detection. Different lower case letters in the same row indicate significant differences between treatments by Dunnett's test ($p < 0.05$).

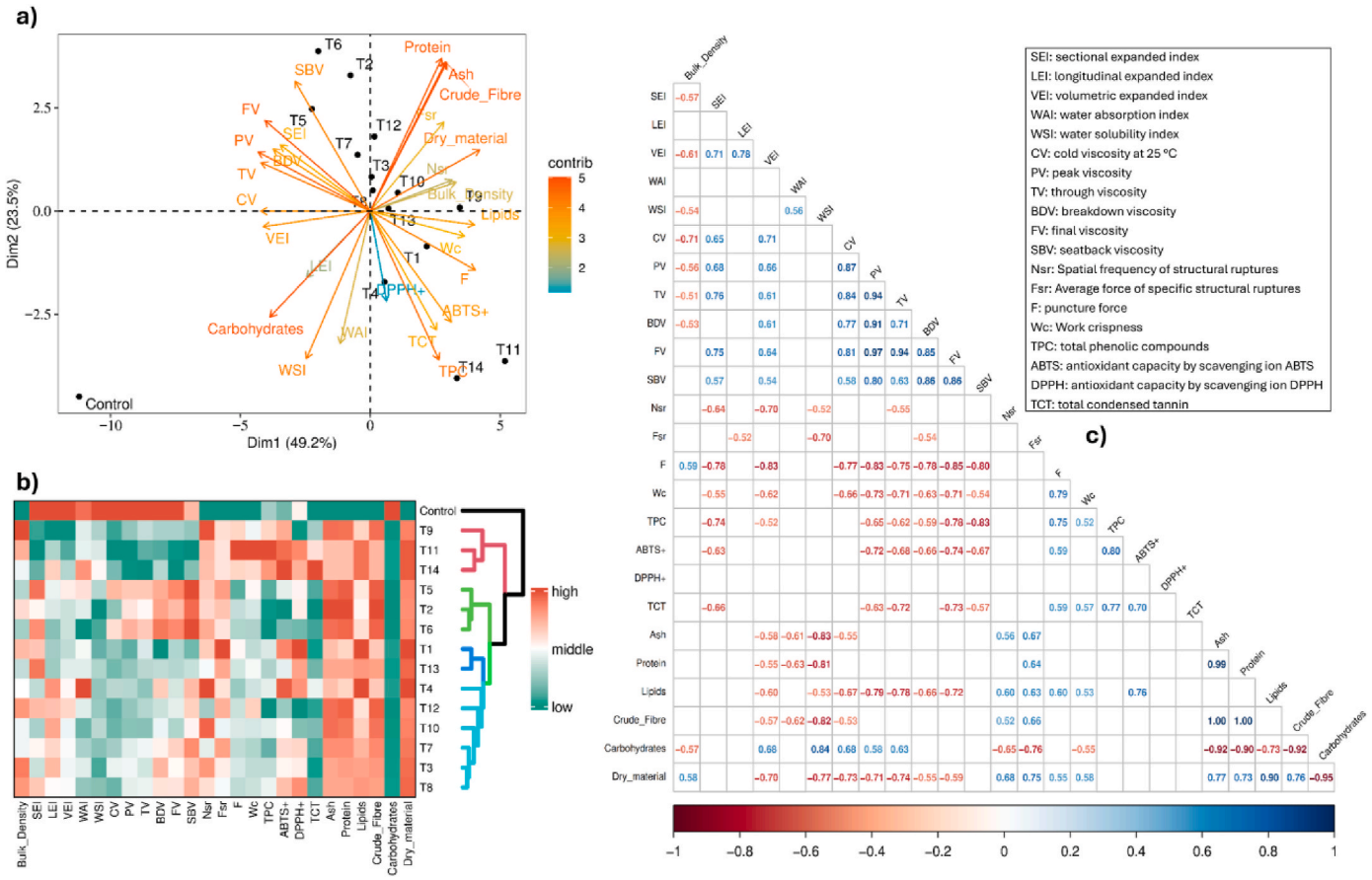

Fig. 5. Principal component analysis (PCA) of enriched extrudates. a-b) bit-plot and heatmap with hierarchical clustering on principal components (HCPC) of samples. c) Person correlogram for parametric variables.

that dry matter is primarily composed of these three components, which showed good correlations with each other, ranging from $0.72 < r \leq 0.89$. While the absence of Andean lupin and pecan nut would result in a reduction in dry matter and a consequent increase in carbohydrates, as indicated by the negative correlation ($r = -0.95$).

Regarding total bioactives and antioxidant capacity, good

correlations were found between TPC with ABTS and TCT, with a correlation coefficient of $0.77 < r \leq 0.81$, showing the direct relationship between total phenolics and condensed tannins concentration, as well as a strong antioxidant activity linked to these compounds. Furthermore, moderate positive correlations were found between ABTS and DPPH, as well as TCT, with a correlation coefficient of $0.56 < r \leq 0.69$. This evidences the relationship between both free radical scavenging mechanisms and the association between condensed tannins and antioxidant capacity, mainly through ABTS. Finally, a moderate and high positive correlation was found between the lipid component and antioxidant capacity by DPPH and ABTS, with correlation coefficients of $0.50 < r \leq 0.76$, respectively.

4. Conclusions

The study demonstrated that the incorporation of whole Andean lupin flour (WLF) and ground pecan nut (GPN) in the production of gluten-free corn-based extrudates significantly improved the nutritional and functional properties of the final product. The results indicated that WLF increased protein, fiber, and ash content, while GPN contributed to higher total phenolic compounds (TPC), condensed tannins (TCT), and antioxidant capacity. The D-optimal mixture design analysis revealed that moisture was the key factor affecting all studied variables, emerging as the mainly influence on the properties of the extrudates. Quadratic models effectively explained the behavior of bioactive compounds, while linear models were adequate to describe other properties such as expansion, mechanical properties, and pasting behavior. The optimized extrudates exhibited a notable 58% increase in protein content and 32% in total phenols, with significant improvements in antioxidant capacity. Moreover, consumer sensory preferences indicated that extrudates with higher GPN content were favored, while those with higher WLF content were tasteless. Finally, it was observed that extrudates containing over 3.2% GPN showed an improved profile of phenolic acids, flavonoids, and catechins, highlighting the potential of this process for developing functional expanded-extrudates with enhanced nutritional and chemoprotective properties. These findings open up new avenues for the development of healthier extruded foods with enhanced health benefits by incorporating alternative sources rich in plant-based proteins and phytochemicals of lipid and phenolic nature.

CRediT authorship contribution statement

Katerin Huamán-Meza: Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Sandra Gonzales-Pérez:** Methodology, Investigation, Formal analysis, Data curation. **Ronald Rimari-Barzola:** Supervision, Resources, Project administration, Funding acquisition. **Davy William Hidalgo Chávez:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis, Data curation. **Carlos W.P. Carvalho:** Writing – review & editing, Resources, Investigation. **Reynaldo J. Silva-Paz:** Writing – original draft, Methodology, Formal analysis. **Carlos Elías-Peñafiel:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Sandra Casimiro-Gonzales:** Writing – review & editing, Methodology, Investigation. **Raúl Comettant-Rabanal:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Ethical guidelines

Ethical guidelines were adhered to in this research. The approval of these guidelines was granted by the Comité Institucional de Ética en Investigación (CIEI) of the Universidad Privada San Juan Bautista, which evaluated and issued the ethical certification No. 1202-2024-CIEI-UPSJB.

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Declaration of competing interest

The authors declared no conflict of interest for this work.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2025.117489.

Data availability

Data will be made available on request.

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