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Potato protein-based meat analogues fortified with upcycled fruit flours: Functional, textural, and antioxidant insights

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ABSTRACT

This study aims to evaluate potato protein (PP) as a substitute for egg white protein (EWP) in vegan formulations. Fruit flours, including orange peel, pineapple peel, and pineapple core, were incorporated to assess their effects on the techno-functional and textural properties, and on the antioxidant potential of plant-based products. Fruit flours improved the performance of PP-based emulsions. More negative zeta potential values and an increased emulsifying stability index were observed in flour-containing formulations. A significant increase in the hardness parameter of the PP-based formulations containing fruit flour was observed, correlated with the higher water-holding capacity. Although fruit flours increased the phenolic content, the enhancement of antioxidant activity was dependent on the fruit flour. Colorimetric analysis showed protein source- and flour-dependent effects, with lower CIELAB values in PP-based samples. Overall, this work highlights the potential of PP and fruit flours for developing functional and sustainable plant-based food products.

1. Introduction

The rise of healthy lifestyle trends and vegetarian/vegan food regimes has driven significant food innovation, with a focus on developing and improving plant-based products, such as emulsion-based products. However, replacing animal-based protein with a vegan analogue is a complex process that requires extensive research to ensure a nutritionally and texturally satisfying product (Chen et al., 2026). Egg white protein (EWP) is widely used in the food industry, due to its excellent emulsifying, gelling, and water-binding properties (Razi et al., 2022); however, the food industry is looking for alternatives to EWP, considering its limitations, including allergenicity, elevated cholesterol levels, incompatibility with vegan and plant-based formulations, price volatility, and sustainability concerns associated with animal-derived ingredients (Laursen et al., 2025).

Potato protein (PP) has gained attention as an emerging plant-based protein because of its valuable nutritional profile and excellent technological properties (Huang et al., 2021; Hussain et al., 2021). The amino acid profile of potato proteins (37%) has been demonstrated to be superior to that of current staple plant-based proteins and even to casein (34%) or egg protein (32%) (Gorissen et al., 2018), containing all essential amino acids and presenting a higher biological value (Beals, 2019). In addition to its high nutritional value, several studies have shown that potato protein has valuable antioxidant and anti-obesity properties (Cheng et al., 2010; Pęksa & Miedzianka, 2021; Camacho et al., 2022; Rahimi et al., 2022). Potato protein mixtures, particularly

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potato peptides, exhibit high water solubility, and foaming and emulsifying capacities, making them suitable for emulsion-based products and comparable to those required of EWP. These technological properties are largely due to the hydrophobic nature of their interactions in an oil/water matrix, their enhanced surface activity, flexibility, and protein composition (Bashash et al., 2024; Schmidt et al., 2018; Van den Wouwer et al., 2025). When aiming to replicate the textural profile of animal meat, gel-forming capacity has also emerged as a critical technological property. PP has demonstrated notable gelling ability as an isolated ingredient or when combined with other proteins, starches, or hydrocolloids (Li, Luo, et al., 2025; Schmidt et al., 2019). A study investigating plant-based protein alternatives reported that PP exhibited higher solubility, and meat analogues formulated with this protein showed enhanced textural parameters compared to a soy protein product (Israeli et al., 2023). However, current literature provides limited evidence of successfully substituting animal proteins entirely with potato protein in meat analogues, particularly in ham-like formulations, which was selected as the model food system for ingredient validation in this work. These challenges likely arise from structural and functional differences between animal and plant proteins, where factors such as protein structure, pH, and processing conditions affect ham-like analogues' stability (Camacho et al., 2022; Lima et al., 2022).

The need to account for these setbacks when sourcing potential ingredients highlights fruit co-product flours as promising ingredients to incorporate in emulsion-based products. Fruit flours are sources of multiple vitamins and bioactive compounds, such as polyphenols and dietary fibers, which support overall health and well-being. Additionally, they can be sustainably sourced from the agrifood industry co-products, such as peels, stems, seeds, and pulp. The study of fruit powders, derived from the fruit itself or its co-products, has been extensively reviewed in the literature, with applications in cereal-based products like bread and cookies, dairy products such as yogurt, and meat-derived products such as burgers (Cao et al., 2025; Hasan et al., 2024; Llatas et al., 2024). Dietary fibers (DFs) can function like hydrocolloids, as they present good water and oil holding capacities, as well as gelling and emulsifying properties (He, Chen, et al., 2022. Camacho et al., 2022). They act as bulking agents, increasing digestion time and the sensation of satiety while contributing to obesity control and reducing glucose absorption (Li, Zeng and Ming, 2025). On the other hand, polyphenolic compounds are known for their biological properties, particularly the antioxidant activity. These bioactive compounds are capable of neutralizing reactive oxygen species (ROS) and reducing oxidative stress, a key contributor to the development of degenerative diseases such as cancer, cardiovascular conditions, and neurodegenerative disorders, including Alzheimer's and Parkinson's disease (Jiang et al., 2021). When considering the characteristics of dietary fibers and polyphenolic compounds, it is important to recognize their mutual influence, which can yield synergistic effects, like enhanced stability and bioavailability or prebiotic properties in gut microbiota fibers fermentation (Sharma et al., 2025; Xue et al., 2024) or antagonistic effects due to competition between DFs and polyphenols for adsorption and binding spots (Liang et al., 2024). Finally, these bioactive compounds can enhance both the textural and technological properties of a plant-based protein, due to their techno-functional attributes: literature reports that the addition of fruit and fruit by-products flours such as dates, banana flowers or jackfruit, as well as soybean insoluble fibers resulted in higher hardness and some cases chewiness in the final meat analogue product, due to the interaction of the flours' fibers with the plant based protein of the formulations (Lian et al., 2025; Priya et al., 2022; Theng et al., 2025).

This study aims to investigate the potential of potato protein as a viable substitute for egg protein in vegan ham-like analogue formulations, as a model emulsion-based food system, and to assess how fruit flours can enhance the techno-functional (emulsion index and stability, and water- and oil-holding capacity) and textural attributes, as well as the bioactive properties of these plant-based products.

2. Materials and methods

2.1. Materials

All reagents and solvents used were of analytical grade. HPLC-DAD and LC-MS solvents, including acetonitrile and methanol, were obtained from ChemLab, Belgium. Ethyl acetate and acetone were obtained from LabChem (Portugal). Folin-Ciocalteau, FRAP, and DPPH reagents, Trolox, chlorogenic acid, (+)-catechin, quercetin-3-*O*-glucoside, and sodium dodecyl sulfate (≥ 98.5%, SDS) were obtained from Sigma-Aldrich. PRIMOR group provided the base ingredients to formulate emulsion-based products, including potato and egg protein, starches, hydrocolloids, and seasonings. Potato protein contains a protein content of 90.5 wt% (dry weight) and a composition of 7 wt% moisture, 0.1 wt% fat, 0.2 wt% fiber, and a residual amount of carbohydrates and sugars (< 0.2 wt%). Both egg white and potato protein were added to the formulation in powder. AgroGrIN Tech kindly donated fruit flours derived from by-products, including orange peel (OPF), pineapple core (PCF), and pineapple peel (PPF).

2.2. Fruit flours characterization

Fruit flours with particle sizes under 100 μm were incorporated into the formulations, and their nutritional composition is detailed in The dried and ground flours were analyzed according to the Standard AOAC methods (Association of Official Analytical Chemists, 1990). Dry weight (DW) was determined by oven drying the samples at 105 °C until constant weight, and moisture content was calculated as the difference between the fresh and dry weight. Ash content (minerals) was determined by incineration in a muffle furnace at 550 °C for 5 h. Total protein content was determined using the Kjeldahl method, applying a nitrogen-to-protein conversion factor of 6.25. Total fat was determined using a Soxhlet extraction system (Soxtec™ 8000, Foss, Denmark), using 5 g of sample packed in a cellulose thimble and extracted with 60 mL of hexane at 90 °C for 3 h (Gómez-García et al., 2021). Total, soluble, and insoluble dietary fiber contents were determined using an enzymatic–-gravimetric method according to AOAC procedures, using a commercial Megazyme dietary fiber assay kit (Megazyme, 2017).Table 1. The dried and ground flours were analyzed according to the Standard AOAC methods (Association of Official Analytical Chemists, 1990). Dry weight (DW) was determined by oven drying the samples at 105 °C until constant weight, and moisture content was calculated as the difference between the fresh and dry weight. Ash content (minerals) was determined by incineration in a muffle furnace at 550 °C for 5 h. Total protein content was determined using the Kjeldahl method, applying a nitrogen-to-protein conversion factor of 6.25. Total fat was determined using a Soxhlet extraction system (Soxtec™ 8000, Foss, Denmark), using 5 g of sample packed in a cellulose thimble and extracted with 60 mL of hexane at 90 °C for 3 h (Gómez-García et al., 2021). Total, soluble, and insoluble dietary fiber contents were determined using an enzymatic–-gravimetric method according to AOAC procedures, using a commercial Megazyme dietary fiber assay kit (Megazyme, 2017).

2.2.1. Techno- and bio-functionalities of fruit flour

2.2.1.1. Water/Oil-holding capacity (WHC/OHC). The water- and oil-holding capacities of fruit flours were determined following the method described by Chau et al. (Chau et al., 1997) with some modifications. For water-holding capacity (WHC) analysis, fruit flours were stirred with deionized water at a 1:20 (*w/v*) ratio for 24 h at room temperature. Oil-holding capacity (OHC) was assessed by mixing the flours with vegetable oil at a 1:20 (w/v) ratio for 1 h at 37 °C. The samples were then centrifuged at 3000 × RCF for 15 min (Dynamica Velocity 14 R Refrigerated Centrifuge, Dynamic Scientific Ltd., Livingston, UK), and the supernatants were removed. The hydrated flour was

Table 1
- Chemical composition of fruit flours expressed as g/100 g dry weight.

Fruit flour	Fat	Minerals	Protein	Total Fiber	Soluble Fiber	Insoluble Fiber	Simple Sugars	Humidity
Orange peel	1.51	3.6	5.7	33.2	10.2	23.0	46.6	4.92
Pineapple core	1.12	4.8	4.1	50.5	0.1	50.4	42.2	7.83
Pineapple peel	0.92	5.6	4.8	46.5	0.2	46.3	31.6	9.34

then weighed, and the WHC and OHC were expressed as grams of water or oil held by a gram of fruit flour, respectively.

2.2.1.2. Glucose adsorption capacity (GAC). The glucose adsorption capacity was determined considering the method described by Ou et al. (Ou et al., 2001) with some modifications. The fruit flours (0.5 g) were mixed with six different glucose solutions (0.0, 5.0, 10.0, 25.0, 50.0, 100.0 mM) and incubated for 6 h at 37 °C with constant stirring. The remaining glucose content after incubation was determined by the GOPOD assay kit (Megazyme, Ireland). GAC was calculated according to Eq. 1:

$$GAC\ (mM) = \frac{C1 - (C2 - C3)}{m} \times \mathrm{V} \quad (1)$$

where C1 is the initial glucose concentration, C2 is the glucose concentration of samples after incubation, C3 is the glucose concentration of samples after incubation with 0 mM glucose solution, m is the weight of fruit flour measured (g), and V is the volume of the sample (L).

2.2.2. Phenolic compounds analysis

2.2.2.1. Phenolic extraction. The phenolic compounds in fruit flours were extracted following a method described by Pérez-Ramírez et al. (Pérez-Ramírez et al., 2018). Duplicates of 5 g of each sample were mixed with 50 mL of a methanol/water solution (50:50, pH 2). The mixtures were stirred at room temperature for 1 h and then centrifuged at 13,000 rpm and 4 °C for 10 min. The supernatants were collected, and the remaining solids were extracted with 50 mL of an acetone/water solution (70:30) under the same conditions. After centrifugation, the supernatants from both extractions were combined. The organic solvents were removed using a rotary evaporator under vacuum at 37 °C, and the final volume was adjusted to 50 mL with Milli-Q water. Liquid-liquid extraction was subsequently performed by mixing 1200 μL of the samples with 1200 μL of ethyl acetate and 600 μL of acetonitrile, vortexed for 10 s (Yang et al., 2017). Samples were centrifuged for 10 min at 8000 rpm, and the organic phases were collected. Extraction was repeated twice; the organic phases were combined and dried in a speed vacuum. The dried residue was resuspended in 100 μL of methanol and 100 μL of Mili-Q water for the HPLC-DAD and LC-DAD/ESI-MS analysis. This procedure, as well as all assays related to phenolic quantification, characterization, and antioxidant performance, was carried out both on the individual fruit flours and on the corresponding lyophilized potato protein-based ham-like formulations containing each fruit flour.

2.2.2.2. Determination of the Total Phenolic Content (TPC). The total phenolic content was determined by the Folin-Ciocalteau method with some modifications (Singleton & Rossi, 1965). Initially, 15 μL of the soluble extracted phenolic compounds (section 2.2.2.1) was mixed with 75 μL of Folin reagent and 500 μL of Mili-Q water in 2 mL Eppendorf tubes and vortexed. Then, 300 μL of Na_2CO_3 and 610 μL of Mili-Q water were added, and the mixture was vortexed again. After 30 min in the dark, 350 μL of each sample mixture was placed in a 96-well plate. For the control, samples were replaced with 15 μL of Mili-Q water. The absorbance was determined at 750 nm at 25 °C (Biotek Powerwave XS, Santa Clara, California, USA), and measurements were performed in triplicate. Results were expressed as mg chlorogenic acid equivalents per g of dry weight (mg CAE/g DW).

2.2.2.3. Quantitative and qualitative phenolic compounds analysis. Quantitative analysis of the soluble extracted phenolic compounds (section 2.2.2.1) was performed using high-performance liquid chromatography with a diode-array detector (HPLC-DAD) on an Elite LaChrom VWR Hitachi system equipped with a Purosphere® STAR Lichrocart C-18 reverse-phase column (150 mm × 4.6 mm, i.d.; 5 μm). A 20 μL aliquot of each sample was analyzed using a mobile phase consisting of solvent A ($HCOOH/H_2O$, 1:99, *v*/*v*) and solvent B (CH_3CN), according to the method reported in the literature, with some modifications (Fernandes et al., 2023). The flow rate was set at 0.5 mL·min^{-1} with the following gradient: 90% A to 10% B over 50 min, transitioning to 100% B in 5 min, followed by a 7-min isocratic gradient at 100% B, and re-equilibration at 90% A for 5 min. The concentrations of phenolic compounds were expressed as mg of chlorogenic acid equivalents (CAE), quercetin-3-O-glucoside equivalents (QE), or catechin equivalents (CE) per gram of dry weight (DW). The phenolic profile identification was achieved using liquid chromatography with diode-array detection and electrospray ionization mass spectrometry (LC-DAD/ESI-MS). The analysis employed the same solvents and flow conditions as described for HPLC-DAD. A Finnigan Surveyor series liquid chromatograph with a Thermo Finnigan Hypersyl Gold C-18 reverse-phase column (150 mm × 4.6 mm, i.d.; 5 μm, Thermo Scientific, Waltham, Massachusetts, USA), at 25 °C, was used for the analysis. Detection was performed between 200 and 700 nm with a Finnigan Surveyor PDA Plus detector. Mass spectrometry was conducted using a Finnigan LCQ DECA XP MAX quadrupole ion trap equipped with an atmospheric pressure ionization (API) source in electrospray ionization (ESI) mode. The vaporizer and capillary voltages were set to 5 kV and 4 V, respectively, with a capillary temperature of 325 °C. Nitrogen was used as both the sheath gas (flow rate of 80 arbitrary units) and auxiliary gas (30 arbitrary units). Spectra were recorded in negative and positive ion modes, spanning *m/z* 120 to 2000. The mass spectrometer performed a series of three scans: a full mass scan, a zoom scan of the most intense ion, and an MS-MS scan of the most intense ion with relative collision energies of 30 and 60 V.

2.2.3. Antioxidant activity

The antioxidant activity of soluble extracted phenolic compounds (section 2.2.2.1) was determined using two methods, namely ferric reducing antioxidant power (FRAP) (Benzie & Strain, 1996) and free radical scavenging activity (DPPH) (Bondet et al., 1997), as indicators of the bioactive potential associated with phenolic compounds present in the fruit by-product flours. In a 96-well plate, 270 μL of diluted FRAP reagent (10 volumes of 300 mM acetate buffer at pH 3.6, 1 volume of 10 mM tripyridyltriazine in 40 mM HCl, and 1 volume of 20 mM $FeCl_3$) was mixed with 30 μL of each sample. Absorbance was measured at 593 nm at 37 °C, between 0 and 4 min. For the DPPH assay, 30 μL of each sample was mixed with 270 μL of DPPH solution (2,2-diphenyl-1-picrylhydrazyl prepared in methanol at 60 μM) in a 96-well plate. The absorbance kinetics were recorded at 515 nm every 5 min for 20 min. Results were expressed in μmol equivalents Trolox/ g DW. Control samples were prepared with Milli-Q water for both methods, and absorbances were measured on a plate reader (Biotek Powerwave XS, Santa Clara, California, USA).

2.2.3.1. QUENCHER assay. QUENCHER procedure was applied to assess the direct antiradical activity of fruit flour, considering the methodology described in the literature (Gökmen et al., 2009; Serpen et al., 2007) with slight modifications. 1.7 mL of DPPH reagent was combined with 2.0 mg of fruit flour, and the mixture was mixed for 20 min to promote the reaction between the insoluble material and the free radical. The samples were centrifuged for 1 min at 13,400 rpm, and the absorbance of the clear supernatant was measured at 515 nm. Results were expressed as μmol Trolox equivalents per g DW.

2.3. Preparation and characterization of potato protein-based emulsions

The emulsifying properties were evaluated to determine the ability of potato protein and fruit flours to stabilize oil–water systems, relevant to ham-like products. The emulsions were prepared by mixing 6 mL of a protein suspension (20 g/L) with 6 mL of commercial sunflower oil using an Ultra-Turrax T25 (Janke & Kunkel GmbH & Co. KG, IKA Labortechnik Staufen, Germany). The process involved mixing for 5 min at 8000 rpm, followed by 4 min at 13,500 rpm (Schmidt et al., 2018). Emulsions containing fruit flours were also prepared, using a ratio of fruit flour:potato protein (1:6). The fruit flours were mixed with potato protein in the aqueous phase to ensure uniform dispersion and interaction with the protein matrix and were then combined with the oil phase. The fruit flours and oil proportions were selected to mimic the protein-to-fruit flour and protein-to-oil ratio in ham-like formulations. The sunflower oil was used without additional refinement to reflect practical food applications. For each potato-based prototype and egg-white protein control, three emulsions were produced.

2.3.1. Particle properties

The particle size and zeta-potential of the emulsions were determined by dynamic light scattering (DLS) and electrophoretic light scattering (ELS) using a Malvern Zetasizer Nano ZS instrument (Malvern Instruments Ltd., UK) at 25 °C. The emulsions were diluted in Milli-Q water at a 1:1000 (*v*/v) ratio. The refractive indices for the protein particles and the dispersion medium were 1.46 and 1.33, respectively (Li et al., 2018).

2.3.2. Emulsifying capacity

The emulsifying properties of the protein-stabilized emulsions were determined based on the procedures of Pearce et al. (Pearce & Kinsella, 1978). The emulsions were diluted 500-fold in two sequential steps: initially, 20 μL of emulsion was mixed with 5 mL of 0.1% SDS solution, followed by a second 2-fold dilution in the same SDS solution using 1 mL of the initial dilution. After mixing for 30 s, the final diluted sample was transferred to a plastic cuvette, and the absorbance was recorded at 500 nm using a UV–Visible spectrophotometer. The emulsifying activity index (EAI) and emulsifying stability index (ESI) were determined using the method developed by Pearce and Kinsella (Pearce & Kinsella, 1978) with some modifications using the following eqs. 2 and 3:

$$EAI\left(\frac{m^2}{g}\right) = \frac{2 \times 2.303 \times A_0 \times DF}{C \times (1-\theta) \times 10000} \tag{2}$$

$$ESI\,(\%) = \frac{A_t}{A_0} \times 100\% \tag{3}$$

Where A_0 is the initial absorbance at 500 nm of the dilute emulsion, DF is the dilution factor, C is the protein concentration (0.02 g/mL), θ is the oil fraction, A_t is the absorbance of the diluted emulsions over time, and t is the time.

2.4. Formulation and characterization

2.4.1. Potato protein-based formulations

The potato protein-based formulations were prepared following a protocol established by the PRIMOR GROUP and processed using a ThermoMix TM6. Protein emulsions described in Section 2.3 were used as the base for the ham-like product formulations. The emulsions were prepared by sequentially mixing water/ice (9% and 9% *w*/w, respectively), oil (4% *w*/w), protein (potato protein or egg white protein, 3% w/w), fruit flours (1% w/w), and starch-based structuring agents (potato starch, 1% w/w). Subsequently, seasoning ingredients including salt (0.30% w/w), dextrose (0.30% w/w), garlic (0.15% w/w), onion (0.15% w/w), vinegar powder (0.14% w/w), and coloring agent (0.30% w/w), as well as hydrocolloids (psyllium, 1.20% w/w) were incorporated. Potato protein-based formulations were tested by incorporating different fruit flours (PP_OPF; PP_PCF; PP_PPF). Ingredients such as water/ice, vegetable oil, starch, spices, coloring agent, and hydrocolloids were incorporated into all the formulations in the same proportion. After mixing the ingredients, the resulting blend was transferred into the synthetic gut, sealed, and refrigerated. The products were then cooked in a water bath at 90 °C until the core temperature of the ham reached 80 °C (≈ 45 min), followed by storage under refrigeration at 4 °C. Textural and colorimetric parameters were analyzed after 4 days of maturation at 4 °C. The ham-like products were then freeze-dried and ground into powder to quantify and characterize phenolic compounds and evaluate antioxidant properties.

2.4.2. Texture profile analysis

The texture profile analysis (TPA) of formulations was conducted using a TA.XT Plus Texture Analyzer (Stable Micro Systems, Godalming, UK), equipped with a 30 kg load cell and an 11 mm plate probe. Cylindrical samples measuring 3 cm in diameter and 3 cm in height were prepared for analysis. The TPA involved a two-compression test with the following parameters: a pre-test speed of 5.0 mm/s, a post-test speed of 5.0 mm/s, a test speed of 2 mm/s, 75% strain, and a trigger force of 0.150 N. A 5-s pause was applied between the first and second compression cycles. Measurements were conducted in triplicate. The TPA parameters, including hardness, cohesiveness, and springiness, were calculated from the force-distance profiles.

2.4.3. Appearance

The formulation's color was evaluated using a portable colorimeter (Lovibond TRA 520 Spectrophotometer, The Tintometer Ltd., UK). The system was calibrated with white and black standards under a D65 light source at a detection angle of 10°. Tristimulus color coordinates (L*, a*, and b*) were measured for the samples in quintuplicate. To differentiate the color of the prototypes containing potato protein and potato protein with fruit flour from the prototype containing egg white protein (used as a commercial reference), the total color difference (ΔE) was calculated according to the following equation:

$$\Delta E = \sqrt{(L-L_0)^2 + (a-a_0)^2 + (b-b_0)^2}$$

where L, a, and b are the lightness, red–green, and yellow–blue coordinates of the sample, respectively, and L_0, a_0, and b_0 correspond to the reference (control) sample. The formulations were placed in transparent Petri dishes, where color measurements were conducted under consistent optical conditions inside a cardboard box covered with black plastic. Additionally, the formulations' visual appearance was documented using a digital camera.

2.5. Statistical analysis

All tests were performed in at least triplicate, with results expressed as the mean ± standard deviation. Statistical data were processed using GraphPad Prism version 8.0 for Windows. One-way analysis of variance (one-way ANOVA) was used to determine statistically significant differences across different experimental groups, using Dunnett's and/or Tukey's tests. Differences were statistically significant at $p < 0.05$.

3. Results and discussion

3.1. Fruit flour

3.1.1. Functionality properties

3.1.1.1. Water and oil holding capacity (WHC/OHC). WHC and OHC are key techno-functional properties of dietary fibers, influencing texture, mouthfeel, emulsion stability, and sensory quality, essential aspects for the successful introduction of fruit flours as food ingredients. Additionally, the physicochemical properties of fiber-rich food ingredients are relevant for their hypoglycemic activity (Jiang et al., 2021). WHC is primarily associated with structural characteristics, such as porosity, surface area, and the abundance of hydrophilic groups of dietary fibers (Xie et al., 2016). In contrast, OHC relates to the hydrophobic interactions of fiber matrices, influenced by surface properties, polysaccharide composition, and overall charge density (Jia et al., 2019). Among the tested fruit flours, pineapple core flour exhibited the highest WHC (6.89 g/g), followed by pineapple peel and orange peel flours (Table 2).

Despite the low soluble fiber content of pineapple core flour (as reported in Table 1), its water-holding behavior aligns with the insoluble fiber content of the flours (50.40, 46.27, and 22.98 g/100 g for pineapple core, pineapple peel, and orange peel flours, respectively), indicating that water retention is predominantly governed by the structural characteristics of the insoluble fraction (e.g., higher porosity or larger surface area). The superior WHC of pineapple core flour may be attributed to its fibrous and porous matrix, facilitating water entrapment through capillary action and hydrogen bonding (Ramasamy et al., 2015; Robertson & Eastwood, 1981). Insoluble fibers, such as cellulose and hemicellulose, possess a network of non-cellulosic cell wall polysaccharides contributing to water retention (Ramasamy et al., 2015). Fibers with high WHC retain more water within the food matrix, improving juiciness, moisture retention during processing, and firmer textures (Huang et al., 2021; Wang et al., 2021). OHC values (1.44–3.62 g/g) followed the same trend, further emphasizing the role of insoluble fibers with hydrophobic domains in interacting with lipid components (Larrosa & Otero, 2021). These properties are particularly relevant for emulsion-based formulations, where oil retention contributes to emulsion stability and desirable mouthfeel (Huang et al., 2021). The values obtained for the three-fruit flour are described in Table 2. Literature indicates WHC and OHC values for orange peel flour ranging from 2.8 to 13.6 g/g DW and 1.8–6.8 g/g DW, respectively (Fan et al., 2022; Nassar & El-Naggar, 2008; Ture, 2023). For pineapple core flour, WHC and OHC values range from 4.5 to 7.6 g/g DW and 1.2–4.2 g/g DW (Hadidi et al., 2020; Sengar et al., 2022; Shiau et al., 2015), respectively, while pineapple peel flour values range from 2.9 to 5.2 g/g DW and 0.7–2.0 g/g DW (Mala et al., 2024; Sengar et al., 2022). The WHC and OHC values obtained in this work align with those reported in the literature, confirming the reproducibility and functional potential.

3.1.1.2. Glucose adsorption capacity (GAC). The glucose adsorption capacity is a significant biofunctionality influenced by the dietary fiber content of the matrix. The GAC is associated with the physical properties of the fiber structure, which may bind to small sugar molecules, decreasing their absorption during digestion and contributing to the most effective way to prevent and control postprandial blood glucose levels (Hauner et al., 2012). The GAC values for the fruit flours are displayed in Fig. 1.

The GAC results indicate concentration-dependent behavior, with higher glucose adsorption observed at increasing glucose concentration across all three fruit flours. This tendency was also confirmed in other studies reported in the literature involving other fruits (Ou et al., 2001; Wang et al., 2020). The highest GAC values were recorded at 100 mM, indicating more efficient interactions between glucose and active adsorption sites at elevated concentrations, particularly for orange peel flour, with values in agreement with the literature (Abirami et al., 2014; Li, Liu, et al., 2022). However, at relevant physiological concentrations (5 and 10 mM) (Hantzidiamantis et al., 2024), the differences in GAC were less accentuated. Nonetheless, it was still possible to observe that orange peel flour presented significantly higher GAC. Key factors influencing GAC include particle size (with smaller particle size enhancing glucose adsorption) (Li, Wang, et al., 2022), surface area, and soluble/insoluble nature of fibers (Abirami et al., 2014; Chau et al., 2003; Dong et al., 2023; Zheng et al., 2019). From the physicochemical profile of the fruit flours, it can be suggested that the higher amount of soluble fibers in OPF may be the distinctive factor that translates into a higher GAC when compared to the other fruit flours. These findings suggest that fruit flours may help reduce postprandial serum glucose levels and contribute to hyperglycemia by glucose adsorption, even at low concentrations.

Table 2
- Water-holding capacity (WHC) and oil-holding capacity (OHC) of fruit flours (g/g, mean ± SD). Values followed by different letters are significantly different ($p < 0.05$).

Fruit flour	Water Holding Capacity	Oil Holding Capacity
Orange peel	3.58 ± 0.05^c	1.44 ± 0.04^c
Pineapple core	6.89 ± 0.42^a	3.62 ± 0.02^a
Pineapple peel	5.47 ± 0.22^b	2.96 ± 0.10^b

3.1.2. Phenolic compounds analysis

3.1.2.1. Phenolic content and antioxidant properties. Phenolic compounds, including flavonoids, phenolic acids, and other polyphenols, play a crucial role in the antioxidant activity of fruits and vegetables, contributing significantly to their health-promoting properties. The values obtained for the total phenolic content (TPC) and antioxidant properties of three fruit flours are detailed in Table 3.

The orange peel flour showed a slightly higher TPC value (26.5 mg CAE/g DW) than both pineapple flours. Regarding orange peel flour, variations in TPC values reported in the literature highlight the influence of orange cultivars and processing techniques on phenolic content, with values between 9.61 and 31.62 mg GAE/g DW dependent on the selected orange varieties and values up to 20 (g/kg) for the best analytical conditions in ultrasound and microwave extractions (Lagha-Benamrouche & Madani, 2013; M'hiri et al., 2015).

In this work, no significant differences were observed in the TPC of pineapple peel and core flours ($p < 0.05$). The composition and purity of the flour extracts can influence TPC results, as non-phenolic compounds acting as reducing agents may interfere with the measurement. Compared to values reported in the literature, the TPC of pineapple peel

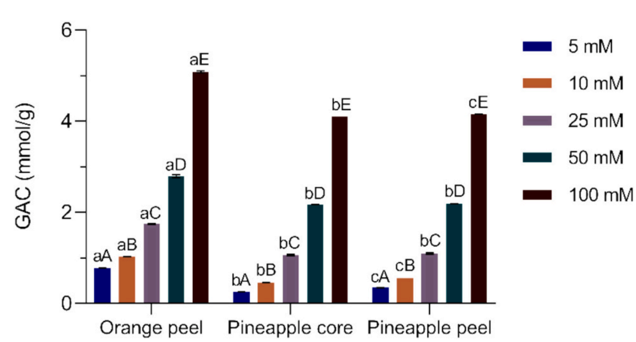


Fig. 1. - GAC of fruit flours (mmol/g). Different lowercase letters indicate statistically significant differences between fruit flours at the same glucose concentration ($p < 0.05$). Different uppercase letters indicate statistically significant differences within the same fruit flour at different glucose concentrations ($p < 0.05$).

Table 3-
Phenolic content and antioxidant properties of fruit flours. Different parameter superscripts in the same line indicate significant differences between samples ($p < 0.05$).

	Orange peel flour	Pineapple core flour	Pineapple peel flour
TPC (mg CAE /g DW)	26.5 ± 0.9^a	12.8 ± 0.4^b	15.2 ± 1.2^b
FRAP (μmol eq Trolox / g DW)	18.5 ± 1.6^a	2.56 ± 0.02^c	14.7 ± 0.2^b
DPPH (μmol eq Trolox / g DW)	2.07 ± 0.02^a	2.0 ± 0.2^a	1.98 ± 0.05^a
QUENCHER (μmol eq Trolox / g DW)	13.9 ± 1.1^a	17.8 ± 0.1^b	16.6 ± 0.2^b

and core flours was lower than that reported by Santos et al., who observed values of 80.42 mg CAE/g DW and 77.61 mg CAE/g DW for peel and core flours, respectively (Santos et al., 2021), Sengar et al., that demonstrated experimental results of 25.91 mg GAE/g DW in pineapple peel and 14.12 mg GAE/g DW in core (Sengar et al., 2022). These variations may arise from different crops, extraction methods, and processing technologies. Environmental factors such as irrigation practices and other cultivation conditions can significantly impact phenolic content (Pliakoni et al., 2010). Nonetheless, a consistent trend observed in this study and the literature is the higher TPC in pineapple peel compared to the core, highlighting the phenolic richness of the outer layers of the fruit (Nordin et al., 2023; Santos et al., 2021; Sengar et al., 2022).

Polyphenols are well-known antioxidant compounds that play a crucial role in food preservation and protection against oxidative stress-related diseases (Rudrapal et al., 2022); however, this work focuses on the bioactive potential of the fruit flours. In this way, FRAP and DPPH assays were performed to evaluate the antioxidant activity of the fruit flour phenolic extracts. Regarding the FRAP assay, the results show that orange peel flour displayed the highest ferric-reducing power, followed by pineapple peel and pineapple core flour, which shows a significant reduction. These results could be correlated with the phenolic content, where the orange peel also demonstrated higher compounds; however, between the pineapple flours, no significant differences in the TPC justified a big difference in FRAP activity. The diversity of the reducing power of the extracts is probably due to the diversity of phenolic compounds present in crude extracts, as well as possible interactions or synergistic effects among the bioactive compounds contained in the fruits. The chelating effect of the ions Fe^{+3} of polyphenols may be related to the highly nucleophilic aromatic rings, as specific chelator groups present within the molecule (Hajimehdipoor et al., 2014; Lagha-Benamrouche & Madani, 2013). Regarding the DPPH assay results, no significant differences were observed between the samples. It is worth noting that antioxidant activity assessments are typically limited to soluble compounds, potentially overlooking the contribution of bound phenolics or insoluble antioxidants. However, many food products contain insoluble components that are not necessarily inert. Functional groups attached to these fractions may contribute to antioxidant activity by neutralizing free radicals within the solvent matrix (Serpen et al., 2007). The QUENCHER assay revealed that the antiradical activity of insoluble fruit flours is primarily exerted at the solid–liquid interface, allowing for the assessment of antioxidant potential not determined by conventional extraction-based methods. The antioxidant activity of the fruit flours, measured using the QUENCHER method, revealed significantly higher values than conventional extract-based assays such as DPPH and FRAP (Table 3). Camacho et al. demonstrated a higher DPPH radical scavenging capacity of insoluble-bound phenolic compounds in orange peel (Camacho et al., 2022). Fernandes et al. also determined a higher antioxidant activity for insoluble pear pomace compared to the soluble phenolic fraction (Fernandes et al., 2023), as well as Gulsunoglu et al., who revealed higher antioxidant activity by DPPH for insoluble-bound phenolic fractions in apple peel, chestnut shell, and black carrot pomace, except the pomegranate peel (Gulsunoglu et al., 2019). The elevated values can be attributed to the nature of the QUENCHER method, which assesses the total antioxidant capacity of the insoluble fraction without requiring solvent extraction. As such, it allows the evaluation of both extractable and non-extractable (bound) phenolic compounds, which are often underestimated by classical methods. Non-extractable phenolics comprise both macromolecular compounds, such as high-molecular-weight proanthocyanidins, and individual phenolic compounds, like phenolic acids, that are bound to macromolecules, primarily to the polysaccharide components of dietary fiber and to proteins (Pérez-Jiménez et al., 2013). Citrus phenolic acids, the main bound-phenolic compounds, show strong antioxidant properties through the dehydrogenation of hydroxyl groups and the effect of ortho-substitution on a benzene ring (Camacho et al., 2022). Although less extractable, these compounds may interact with the protein matrix, contributing to dual functionality: nutritional enhancement and improvement of oxidative stability of the final product (He, Chen, et al., 2022; Pérez-Jiménez et al., 2013). Furthermore, their presence could promote extended shelf-life, offer added health benefits such as anti-inflammatory or anti-obesity effects, and enhance gut health (Liu et al., 2024; Pérez-Jiménez et al., 2013). These results highlight the potential of upcycled fruit flours as natural antioxidants in food formulations, offering an alternative to synthetic additives.

3.1.2.2. LC-DAD/ESI-MS identification. Phenolic compounds in the fruit flours were quantified by HPLC-DAD and tentatively identified using LC-MS (chromatographic information detailed in the supplementary material). Orange peel flour exhibited a complex chromatographic profile, predominantly composed of phenolic acids, including isomers of *p*-coumaroylquinic acid characterized by $[M-H]^-$ ions at m/z 337 and an MS^2 fragment ion at m/z 190 (López-Salas et al., 2022; Vilas-Boas et al., 2020). Other compounds include protocatechuic acid-glycoside ($[M-H]^-$ m/z 315, MS^2 153) (Vilas-Boas et al., 2020), feruloylquinic acid derivatives showing a molecular ion $[M-H]^-$ m/z 363 and a fragmentation pattern of MS^2 323 (Cebadera et al., 2020; Vilas-Boas et al., 2020), and feruloyl hexose derivatives ($[M-H]^-$ m/z 355, MS^2 152) (Campos de Siqueira et al., 2019;Cebadera et al., 2020; López-Salas et al., 2022). Among flavonoids, flavanones were the most abundant, with naringin ($[M–H]^-$ m/z 579, MS^2 271) and hesperidin ($[M–H]^-$ m/z 609, MS^2 301) being tentatively identified. These compounds are typical flavanones found in citrus fruits (Cebadera et al., 2020; Legua et al., 2022; Shehata et al., 2021). Other identified flavonoids included apigenin-7-*O*-(6″-malonyl-apiosyl glucoside ($[M-H]^-$ m/z 649, MS^2 605) (Russo et al., 2015) and kaempferol-3-*O*-rutinoside ($[M - H]^-$ m/z 593 and fragmentation MS^2 285) (Cebadera et al., 2020; López-Salas et al., 2022).

Pineapple core and peel flours exhibited similar chromatographic profile with a maximum of 12 peaks, including compounds such as diferuloylspermidine ($[M-H]^-$ m/z 496, MS^2 346) (Difonzo et al., 2019; Lourenço et al., 2021), quercetin hexoside ($[M-H]^-$ m/z 463, MS^2 301) (Lourenço et al., 2021; Steingass et al., 2015), and dicaffeoylglycerol ($[M-H]^-$ m/z 415, MS^2 253, 179, 161, 135) (Ma et al., 2007; Steingass et al., 2015). In pineapple core flour, peak 4 was identified as caffeoylisocitrate ($[M-H]^-$ m/z 353, MS^2 191, 173, 154, 110) (Difonzo et al., 2019; Steingass et al., 2015), and peak 5 as tetragalloylglucose ($[M-H]^-$ m/z 787, MS^2 617, 635) (Wyrepkowski et al., 2014). Pineapple peel flour contained 3-(3,4-dihydroxyphenyl)lactic acid ($[M-H]^-$ m/z 197, MS^2 179, 134) (Liu et al., 2007; Oliveira-Alves et al., 2017), caffeoyl glycerol ($[M-H]^-$ m/z 253, MS^2 135, 161, 178) (40), apigenin 6,8-di-C-pentoside ($[M-H]^-$ m/z 533, MS^2 413) (Picariello et al., 2025), and feruloyl hexoside ($[M-H]^-$ m/z 355, MS^2 235, 265, 295) as main components (Steingass et al., 2015).

3.2. Emulsion analysis

3.2.1. Particle size and zeta-potential

The particle size and zeta potential of the emulsions are presented in Fig. 2 (a). The average particle sizes of the emulsions stabilized with egg white protein and potato protein were 1927 and 1042 nm, respectively. The differences in food-grade proteins in reducing the droplet size during homogenization can be attributed to various factors, including their surface loads, adsorption rates, ability to decrease interfacial tension, and ability to protect droplets from coalescence. Being more surface-active under certain pH and ionic conditions, potato protein may have adsorbed more rapidly to the oil–water interface, leading to finer droplet dispersion during homogenization (McClements, 2015). The incorporation of fruit flours had varying effects depending on their composition. Orange peel flour did not significantly affect droplet size (975 nm), which could suggest a synergistic interaction with potato protein at the interface, possibly due to its content of soluble fibers or polyphenols that stabilize the interfacial layer. In contrast, pineapple core and peel flours led to increased droplet sizes (2161 and 1597 nm, respectively), potentially due to the presence of insoluble fibers or competing surface-active compounds that hindered protein adsorption or disrupted the interfacial film, resulting in larger droplet coalescence.

The zeta potential values of the emulsions provide additional insight into the electrostatic stability of the dispersed particles. The emulsion stabilized with egg white protein and potato protein exhibited negative zeta potential (−30.5 and − 32.6 mV, respectively, Fig. 2 a), indicating strong electrostatic repulsion between particles and, consequently, greater colloidal stability. Interestingly, adding fruit flours to the potato protein-stabilized emulsions resulted in more negative zeta potential values (ranging from −35.5 to −38.7 mV), without significant differences between orange and pineapple peel flours. The components of fruit flours can adsorb at the particle interface or interact with the protein matrix, enhancing the net surface charge and potentially improving emulsion stability. It highlights the role of fruit flour constituents in modulating interfacial interactions and colloidal behavior. Hu and Xiong reported a reduction in average droplet size accompanied by an increase in absolute zeta potential in emulsions stabilized by potato protein alone and by potato protein–chitosan (PP/CS) complexes. This behavior was strongly dependent on the protein-to-chitosan ratio, indicating that electrostatic interactions between the biopolymers play a key role in interfacial stabilization (Hu & Xiong, 2022). Similarly, Hu and Zhang observed that the mean droplet size of potato protein-stabilized emulsions markedly decreased from 5102.50 nm to 784.90 nm and 1268.50 nm upon the addition of 0.2% and 0.4% chitosan (CS), respectively, while the zeta potential increased from 40.63 mV to 48.50 and 53.73 mV. This might be attributed to the fact that the CS addition reduced the interfacial tension of PP or the reason that the CS adhered to the surface of the PP, leading to an increase in electrostatic repulsion between emulsions, preventing the droplets from aggregating (Hu & Zhang, 2022). Han et al. demonstrated that complexation of potato protein with pectin significantly improved emulsion stability, particularly at pH 5, where the zeta potential became more negative compared to potato protein alone. Overall, these studies highlight that the simultaneous reduction in droplet size and increase in the absolute zeta potential, promoted by protein–polysaccharide interactions, are key factors governing the physical stability of potato protein-based emulsions (Han et al., 2023).

3.2.2. Emulsifying properties

The ability of a protein to form and stabilize an emulsion over time was determined by applying the emulsifying activity index (EAI) and the emulsion stability index (ESI), respectively. The emulsifying capacity of potato protein was evaluated independently and in combination with three fruit-derived flours. The results are presented in Fig. 2 (b). Egg white protein exhibited higher emulsifying activity (23.3 m^2/g) than potato protein (10.4 m^2/g). The incorporation of by-product flours did not result in any significant changes to the emulsifying capacity of potato protein ($p < 0.05$). This outcome suggests that the complex composition of the flours, which includes insoluble fiber and phenolic compounds, did not affect the protein's ability to adsorb at the oil–water

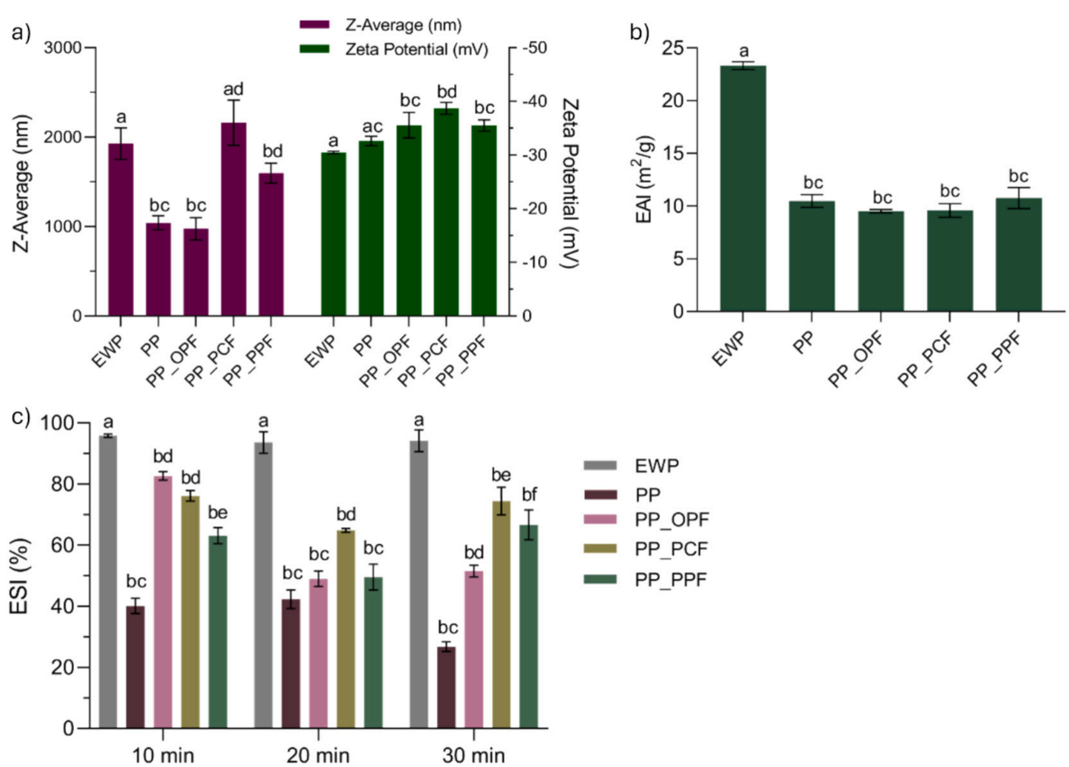


Fig. 2. - (a) Particle size and zeta potential measurements of the emulsions. (b) Emulsifying activity index (EAI) and (c) emulsion stability index (ESI) of egg white and potato protein-based formulations. Different letters indicate significant differences among groups ($p < 0.05$).

interface or stabilize emulsions. From a formulation perspective, fiber enrichment can be achieved without compromising the protein's emulsifying functionality. A consistent improvement in emulsion stability over time was observed (Fig. 2 c), with a more pronounced effect from pineapple core flour. In all flour-containing systems, the emulsions maintained their integrity more effectively over a 30-min monitoring period than those prepared with potato protein alone. This enhanced stability suggests a possible synergistic effect between potato protein and the constituents of fruit flours. Possible mechanisms include physical stabilization by fiber particles dispersed in the continuous phase, as well as increased viscosity, which may have constrained droplet coalescence and, consequently, enhanced emulsion stability (Ou et al., 2001; Wang et al., 2020). The interaction between protein and fiber may serve as a physical barrier, protecting oil droplets from flocculation while ensuring enhanced stability over time (Ou et al., 2001; Li, Wang, et al., 2022). Furthermore, some interactions between fiber-bound phenolic compounds and the protein matrix cannot be excluded, as such interactions have been previously reported to influence interfacial film strength and improve emulsion stability (Abirami et al., 2014; Hantzidiamantis et al., 2024). These findings are particularly relevant when considering the design of plant-based emulsified products, where long-term stability is often a limiting factor. On the other hand, studies reported in the literature generally indicate improvements in both the EAI and ESI of potato protein–based systems. Hu and Xiong showed that the addition of chitosan (0.1–0.3%) to potato protein significantly enhanced emulsifying activity, which was attributed to a reduction in interfacial tension and, consequently, to an increased adsorption of the protein–polysaccharide complexes at the oil–water interface (Hu & Xiong, 2022). Similarly, the incorporation of pectin markedly improved EAI and ESI values, increasing by 27.71% to 68.78% and 35.16% to 66.07%, respectively, when the mass ratio of potato protein to pectin ranged from 1:0 to 1:1. This improvement was associated with an expansion of the adsorption area of PP at the oil–water interface, while the presence of pectin inhibited droplet flocculation and enhanced the structural rigidity of the electrostatic complexes (Han et al., 2023).

3.3. *Potato-based ham-like formulations*

3.3.1. *Texture profile analyses (TPA)*

The textural properties of the different formulations are summarized in Table 4. Replacing egg white protein (EWP) with potato protein (PP) and incorporating vegetable fibers led to notable modifications in the textural profile of the ham-like formulations. A slight but significant decrease in hardness ($p < 0.0001$) was observed in the PP-based samples compared to the EWP control. These results suggest that potato protein may have a lower capacity to form intermolecular bonds, or alternatively, may have a different protein composition or contain other components that affect its ability to form a three-dimensional gel network. The addition of fruit flours significantly increased hardness, resulting in prototypes with values comparable to or exceeding those of the control. This effect can be attributed to the high insoluble dietary fiber content in fruit flours, which likely reinforces the matrix by acting as a structural filler. Additionally, the high water-holding capacity (WHC) of fruit flours likely contributed to reduced cooking losses and improved emulsion stability, further supporting matrix hardness (Ou et al., 2021; Wang et al., 2020). In contrast, substituting EWP with PP markedly compromised other texture attributes, particularly those reflecting the elastic and cohesive behavior of the gel matrix. The resilience of PP-based formulations, which reflects how well the gel matrix recovers after the first compression, was significantly reduced (≈ 40% compared to EWP). This effect may be explained by the greater tendency of PP-based prototypes to fracture under stress, compromising their ability to withstand successive deformation cycles (Li et al., 2022). Similarly, springiness and chewiness values decreased, indicating that PP-based formulations exhibited a diminished capacity for elastic recovery. Among these, the formulation containing orange peel flour exhibited the lowest springiness, whereas those with pineapple core and peel flours showed higher chewiness. Cohesiveness was also reduced by approximately 35%, even in the presence of fruit flours, although no significant differences were observed among the various PP-based formulations. Taken together, these findings suggest that while fruit flours effectively restore or enhance mechanical firmness (hardness), they have limited ability to compensate for the loss of elasticity and structural integrity, which are primarily governed by the protein network. PP forms weaker viscoelastic networks compared to EWP, and the fruit flours do not appear to meaningfully reinforce elastic and cohesive properties. Several studies have reported the incorporation of potato protein (PP) with different food ingredients as a strategy to improve potato protein textural properties. Zhou et al. investigated the effect of different additives on the textural properties of potato protein gels, including transglutaminase, salt, and pectin. Transglutaminase and salt consistently enhanced gel strength, significantly increasing hardness, cohesiveness, resilience, and chewiness, with salt promoting stronger gel networks by reducing electrostatic repulsion during gelation and transglutaminase inducing covalent crosslinking between protein molecules. Pectin effect was concentration-dependent: low levels (up to ~0.25%) improved hardness and other textural parameters, whereas higher concentrations led to a reduction in gel strength. At elevated levels, pectin decreased firmness while increasing gel malleability and promoting a more porous and fibrous microstructure (Zhou et al., 2023). Ryu et al. also studied the effects of calcium salt type on the structure and texture of potato protein-alginate composite gels (Ryu et al., 2024). The gel strength increased in the following order: $CaCO_3 < Ca_3PO_4 < CaHPO_4$. This change in gel strength was mainly related to differences in the pH. No significant differences were observed among the composite gels before heating, except for slightly lower springiness in $CaHPO_4$ induced gels. After heating, distinct behaviors emerged: the hardness of $CaCO_3$ induced gels decreased, likely due to the formation of CO_2 bubbles, whereas the hardness of the other composite gels increased, which was attributed to potato protein denaturation and aggregation. Despite this increase, these gels exhibited similar hardness values after heating. Additionally, heating led to a general decrease in springiness, cohesiveness, and chewiness across all samples, as observed in this work with fruit flours (Ryu et al., 2024). Santhapur et al. investigated the potential of creating hybrid meat analogs by combining mycoprotein (MCP), a mycelium-based protein, with potato protein (PP) (Santhapur et al., 2024). The hardness and chewiness of the hybrid gels were greater than those of the equivalent potato protein gels. The hardness of the 15% MCP + 15% PP

Table 4
- Texture profile analysis (TPA) of control formulation containing egg white protein (EWP), potato protein (PP), and potato protein fortified with fruit flour, including orange peel flour (PP_OPF), pineapple core flour (PP_PCF), and pineapple peel flour (PP_PPF). Different parameter superscripts in the same column indicate significant differences from the control of egg white protein and between PP-based formulations.

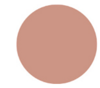
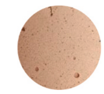
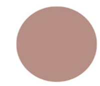
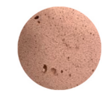
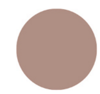
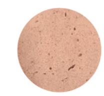
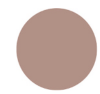
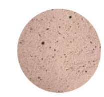
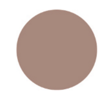
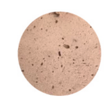
Formulation	Hardness (N)	Resilience (%)	Cohesiveness	Springiness	Chewiness (N)
EWP	110 ± 3^{a}	15.48 ± 0.01^{a}	0.41 ± 0.02^{a}	0.72 ± 0.02^{a}	31 ± 1^{a}
PP	86 ± 1^{bc}	6.30 ± 0.01^{bc}	0.271 ± 0.006^{bc}	0.48 ± 0.01^{bc}	10.4 ± 0.6^{bc}
PP_OPF	121 ± 3^{bd}	6.46 ± 0.01^{bc}	0.270 ± 0.003^{bc}	0.32 ± 0.01^{bd}	10.4 ± 0.7^{bc}
PP_PCF	122 ± 3^{bd}	6.67 ± 0.01^{bc}	0.269 ± 0.006^{bc}	0.45 ± 0.02^{bc}	14.6 ± 0.9^{bd}
PP_PPF	127 ± 3^{bd}	6.04 ± 0.01^{bc}	0.248 ± 0.003^{bc}	0.42 ± 0.01^{bc}	13.3 ± 0.2^{bd}

gel was 16.4 ± 1.7 kPa, whereas that of the 15% PP gel was only 6.2 ± 0.3 kPa. Thus, the addition of the MCP increased the strength of the potato protein gels by nearly 165%, probably because the MCP formed an interpenetrating network with the PP, or the components in the MCP reinforced the molecular interactions between the PP molecules. There was no strong dependence on the resilience or cohesiveness of the hybrid gels on protein content, but the values of the hybrid gels were significantly higher than those of the pure PP gels. Li et al. formulated PP with high acyl or low acyl gellan gum (HA-GG or LA-GG). The textural properties of the composite hydrogels differed depending on whether high-acyl (HA-GG) or low-acyl gellan gum (LA-GG) was used. For HA-GG systems, increasing the GG concentration (0.8% vs. 0.4%) resulted in higher hardness, resilience, cohesiveness, and springiness. However, when potato protein (PP) was incorporated, hardness generally increased with protein concentration, while resilience, cohesiveness, and springiness decreased compared to HA-GG alone. In contrast, LA-GG systems showed a concentration-dependent behavior. At low LA-GG levels (0.1%), hardness increased significantly with increasing PP concentration, whereas resilience, cohesiveness, and springiness were only slightly affected. Conversely, at high LA-GG concentration (0.8%), the hydrogel without PP exhibited the highest hardness, and further addition of PP reduced hardness, suggesting interference with LA-GG crosslinking. Under these conditions, resilience, cohesiveness, and springiness increased with increasing PP concentration, indicating improved recovery after deformation compared to LA-GG alone (Li et al., 2025). Priya et al. developed vegan sausages incorporating banana florets and immature jackfruit to evaluate the concentration effect on their quality attributes, such as sensory, textural, and physicochemical characteristics. The developed sausages had higher hardness, gumminess, and chewiness with raw jackfruit extract compared to the vegan sausage control and banana florets formulations (Priya et al., 2021). Similar effects of fiber incorporation have been reported in pea protein–based high-moisture meat analogues (Theng et al., 2025). The addition of date fruit (*Phoenix dactylifera L.*) dietary fiber (5–10%) led to reduced elastic properties and the formation of a more brittle network, accompanied by increased hardness and chewiness, due to protein–fiber and fiber–fiber interactions that altered the protein matrix organization. This work also supports the concept that insoluble fiber fractions can significantly influence matrix rigidity and network structuring in plant-based meat analogues.

3.3.2. Colorimetric properties and appearance

The color and appearance of ham-like products are critical factors in consumer acceptance, as contemporary consumers tend to favor foods that closely resemble natural products in both look and texture. The results for the CIELab coordinates and the visual characteristics of the ham-like formulations are presented in Table 5. The color parameters (L*, a*, and b*) of the various ham-like formulations reveal significant differences between the egg white protein (EWP) control and the potato-based protein (PP) formulations, both with and without the incorporation of fruit flours. These differences can be attributed to the distinct color characteristics of the protein matrices and the fruit flours. Egg white protein (EWP) exhibits a lighter, more vivid color compared to the brownish hue of potato protein (PP), resulting in higher lightness values for the EWP control compared to the PP-based formulations. Furthermore, a significant decrease in the a* (redness) and b* (yellowness) coordinates was observed using PP, particularly when fruit flours were incorporated. Some studies have suggested that the polyphenols present in these fruit flours contribute to the darker color, as evidenced by lower CIELab coordinate values, likely due to oxidation processes (Aboshora et al., 2019; Ajila et al., 2008). The resulting prototypes presented color differences perceptible to the Human eye (ΔE greater than 5) (Mokrzycki & Tatol, 2011), obtaining a lower difference in the absence of fruit flour and a higher difference using pineapple core flour. Ryu et al. also verified a decrease in the a* and b* CIELab coordinates in the preparation of potato protein-alginate hydrogels with the impact of different insoluble calcium salts (Ryu et al., 2024), although they observed an increase in the L* coordinate as a result of the protein degradation after heating the composite gels. Zhou et al. observed that increasing the pectin and salt (NaCl) concentration led to an increase in the lightness (L*), redness (a*), and yellowness (b*) of the protein gels due to changes in the density and dimensions of the protein-rich heterogeneities in the PP gels. On the other hand, transglutaminase did not cause any light scattering or appearance of the PP gels (Zhou et al., 2023). Priya et al. demonstrated that the incorporation of banana florets in vegan sausages decreases all CIELAB color coordinates, as observed for the fruit flours in the present study, whereas raw jackfruit increased all colorimetric parameters (Priya et al., 2021). Similarly, Theng et al. observed that the incorporation of dietary fiber in pea protein-based systems has been associated with decreased L* and b* values, resulting in darker and less yellow products, confirming the impact of fiber-rich ingredients on product appearance (Theng et al., 2025).

Table 5
- CIELab coordinates (L*, a*, and b*) and visual aspect of egg white and potato-based protein formulations. Different parameter superscripts in the same column indicate significant differences from the control of egg white protein.

Formulation	L*	a*	b*	ΔE	RGB	Visual aspect
EWP	65 ± 2[a]	17.5 ± 0.4[a]	15.3 ± 0.5[a]	–		
PP	62 ± 1[bc]	12.5 ± 0.4[bc]	9.4 ± 0.5[bc]	6.9 ± 0.4		
PP_OPF	61 ± 1[bc]	10.0 ± 0.2[bd]	10.1 ± 0.4[bc]	8 ± 1		
PP_PCF	62 ± 1[bc]	9.7 ± 0.4[bd]	8.9 ± 0.5[bd]	11 ± 1		
PP_PPF	59 ± 1[bd]	9.2 ± 0.2[bd]	9.8 ± 0.5[bc]	8.7 ± 0.9		

3.3.3. Phenolic profile and antioxidant properties of vegan products

Considering that elevated temperatures can alter the phenolic composition, the formulation's total phenolic content, individual phenolic profile, and antioxidant activity were evaluated following thermal processing (Incorporating fruit flours into the formulations led to a notable increase in total phenolic content (TPC), with orange peel flour producing the highest enhancement (≈ 50%) compared to the potato protein-based control. A more modest increase (≈ 20%) was observed with pineapple core flour. Nevertheless, compared to the original TPC values of the fruit flours (Table 3), a substantial reduction was evident following their inclusion in the ham-like formulations, likely due to thermal degradation or interactions within the matrix. HPLC analysis further revealed a general decrease in the levels of various phenolic classes. Although the chromatographic profiles of the fruit flours and their corresponding potato protein-based formulations appeared similar, identifying individual phenolic compounds was more challenging in the ham-like matrices. Several polyphenols detected in the original flours were not identified in the final formulations, likely due to their sensitivity to heat and the influence of food matrix interactions. Thermal processing, in particular, may have contributed to the degradation or transformation of phenolic compounds. Additionally, matrix complexity, pH, salt content, and the presence of native polyphenols in potato protein may have interfered with the detection of fruit-derived phenolics through co-elution or signal suppression (Chen et al., 2014). Regarding antioxidant activity, the PP_PCF formulation exhibited the lowest DPPH and FRAP assay values. However, no significant correlation was observed between total phenolic content and antioxidant activity. This discrepancy may reflect differences in the chemical structure, reactivity, and synergistic interactions of phenolic compounds in the flours, highlighting the complexity of predicting antioxidant capacity solely based on total phenolic content.

Table 6). Incorporating fruit flours into the formulations led to a notable increase in total phenolic content (TPC), with orange peel flour producing the highest enhancement (≈ 50%) compared to the potato protein-based control. A more modest increase (≈ 20%) was observed with pineapple core flour. Nevertheless, compared to the original TPC values of the fruit flours (Table 3), a substantial reduction was evident following their inclusion in the ham-like formulations, likely due to thermal degradation or interactions within the matrix. HPLC analysis further revealed a general decrease in the levels of various phenolic classes. Although the chromatographic profiles of the fruit flours and their corresponding potato protein-based formulations appeared similar, identifying individual phenolic compounds was more challenging in the ham-like matrices. Several polyphenols detected in the original flours were not identified in the final formulations, likely due to their sensitivity to heat and the influence of food matrix interactions. Thermal processing, in particular, may have contributed to the degradation or transformation of phenolic compounds. Additionally, matrix complexity, pH, salt content, and the presence of native polyphenols in potato protein may have interfered with the detection of fruit-derived phenolics through co-elution or signal suppression (Chen et al., 2014). Regarding antioxidant activity, the PP_PCF formulation exhibited the lowest DPPH and FRAP assay values. However, no significant correlation was observed between total phenolic content and antioxidant activity. This discrepancy may reflect differences in the chemical structure, reactivity, and synergistic interactions of phenolic compounds in the flours, highlighting the complexity of predicting antioxidant capacity solely based on total phenolic content.

4. Conclusions

In this study, plant-based ham-like products were developed using potato protein and fruit flours obtained from food industry co-products. This work was designed for a niche market - the vegan market, where potato protein was demonstrated as a possible alternative to egg white protein, contributing to developing health-oriented, meat-analogue products. In addition to the significant amount of phenolic compounds in the vegan ham-like formulation, as well as dietary fibers, a potential advantage of the introduction of fruit flour is the improvement of the textural parameters, particularly the hardness of the formulation, since texture enhancement is a big challenge when this type of product is developed. The presence of fruit flour helps to fine-tune products' water- and oil-holding capacity, texture, and emulsification properties. The compatibility between the ingredients is advantageous, particularly when aiming to design meat analogue systems that align with current clean-label and sustainability trends. The ability to incorporate upcycled materials without negatively affecting the core functional properties of the matrix adds significant value from both a nutritional and processing standpoint. The potato-protein formulation with pineapple peel flour showed higher values for hardness, although all formulations exhibited values closer to the control egg white protein. Although different colors were obtained, the appearance of these potato protein-based formulations always resembled the red/pink typical ham coloration. However, future studies should include evaluating these products' sensory attributes and consumer acceptance. Further investigation into other textural parameters, such as cohesiveness, springiness, and chewiness, through ingredient ratio optimization or the inclusion of other plant-based ingredients, would be valuable. Nutritional analysis, lipidic oxidation prevention, bioaccessibility of compounds, and protein digestibility studies are also key next steps for this work.

Table 6
- Phenolic composition and antioxidant activity of potato protein formulations. Different parameter superscripts in the same column indicate significant differences from the potato protein formulation without fruit flour ($p < 0.01$).

Formulation	TPC (mg CAE /g DW)	DPPH (μmol eq Trolox / g DW)	FRAP (μmol eq Trolox / g DW)
PP	0.38 ± 0.03^{a}	0.162 ± 0.001^{a}	0.255 ± 0.002^{a}
PP_OPF	0.66 ± 0.04^{bc}	0.17 ± 0.04^{ab}	0.317 ± 0.002^{bc}
PP_PCF	0.46 ± 0.01^{ad}	0.146 ± 0.001^{ab}	0.28 ± 0.01^{ad}
PP_PPF	0.58 ± 0.04^{bc}	0.22 ± 0.02^{ab}	0.42 ± 0.01^{be}

CRediT authorship contribution statement

Ana Rita Pereira: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Vasco Trincão da Silva:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Duarte Torres:** Writing – review & editing, Methodology. **Ana A. Vilas-Boas:** Writing – review & editing, Methodology. **Débora A. Campos:** Writing – review & editing, Methodology. **Inês Cruz:** Methodology. **Adriana Ferreira:** Methodology. **Nuno Mateus:** Writing – review & editing, Project administration. **Victor de Freitas:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Ana Fernandes:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2026.150251.

Data availability

Data will be made available on request.

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