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RESEARCH

Nutritional and sensory evaluation of a formulated Hanwoo beef patty and commercial plant-based alternatives

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Abstract

Due to population growth and rising demand for sustainable proteins, plant-based meat analogs (PBMAs) have drawn attention as alternatives to traditional meat. This study compared nutritional and sensory properties of Hanwoo beef patties (HP) and PBMA patties (PP), analyzing proximate composition, total calories, cholesterol, minerals, sugars, fatty acids, and amino acids. The nutritional analysis showed that HP contained significantly higher levels of crude protein, fat, and total calories compared to PP, while carbohydrates were only detected in PP. The cholesterol content was 70.46 mg/100 g in HP, whereas no cholesterol was detected in PP. Ca, P, and Cu were not significantly different between HP and PP, but Fe, K, Mg, and Na were significantly higher in PP. However, zinc content was higher in HP than in PP ($p<0.05$). Regarding sugars, fructose, glucose, sucrose, and total sugar content were significantly higher in PP compared to HP. HP had significantly higher levels of oleic, saturated, and monounsaturated fatty acids, while PP showed a significantly higher polyunsaturated-to-saturated fatty acid ratio. PP had lower levels of lysine but higher umami-related glutamic and aspartic acid than HP ($p<0.05$). Multivariate analysis revealed distinct nutritional profiles between HP and PP, with arachidic acid as the key marker. Sensory evaluation showed that HP received higher scores for appearance, color, taste, flavor, and overall acceptability, whereas PP exhibited significantly higher off-flavor scores. These results offer key nutritional data on HP and PP, helping build consumer trust and support the adoption of sustainable food alternatives globally.

Keywords Hanwoo · Plant-based meat analog · Patty · Nutrition · Sensory characteristics

Introduction

Quality of meat is influenced by a variety of factors, including nutritional value, safety, and sensory characteristics, all of which play critical roles in shaping consumer preferences (Jang et al., 2019). Meat has always been an essential source of protein and bioavailable micronutrients, including zinc, heme iron, and B vitamins, and it has played a significant role in human development (Xie et al., 2022a). Specifically, Hanwoo, a native Korean cattle breed, is noted for offering potential health advantages owing to its relatively lower cholesterol levels and higher omega-3 fatty acid content compared to other beef breeds. Hanwoo is also renowned for its tender texture, rich juiciness, and distinct flavor, all of which contribute to its high market value and strong consumer demand (Lee et al., 2014).

Patties, processed meat products commonly used in hamburgers, are a cornerstone of the global fast food industry. As of 2020, the global fast food market was valued at approximately USD 862 billion, with the "Burger & Sandwich"

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segment accounting for 36% of this market (Petrat-Melin & Dam, 2023). Various food processing techniques, such as grinding, heating, fermentation, smoking, drying, canning, and extrusion, are employed in the production of patties and other meat products to improve nutrient bioavailability, extend shelf life, and enhance both functional and sensory attributes (Augustin et al., 2016).

According to the Food and Agriculture Organization, global meat consumption is projected to reach 455 million tons by 2050, driven by continued population growth (Alexandratos and Bruinsma, 2012). However, from a sustainability standpoint, the increasing demand for animal-derived proteins has raised significant environmental and ethical concerns (Xie et al., 2022b). Livestock farming imposes significant environmental pressure, such as land degradation, deforestation, and loss of biodiversity, with approximately 7 kg of plant-derived feed needed to yield only 1 kg of meat (Bakhsh et al., 2021). These challenges have fueled increasing interest in alternative proteins, especially plant-based meat analogs (PBMAs), which are designed to mimic the texture, flavor, appearance, and nutritional characteristics of traditional meat (Xie et al., 2022a; Yang et al., 2023).

Nutritional labeling plays a vital role in guiding consumers towards informed dietary decisions, especially for individuals managing chronic conditions such as hypertension, hyperlipidemia, and type 2 diabetes (Post et al., 2010). In South Korea, the Ministry of Food and Drug Safety (Ministry of Food and Drug Safety (MFDS), 2019) mandates that nutrition labels include information on calories, sodium, carbohydrates, total sugars, lipids, trans- and saturated fatty acids, cholesterol, and protein, alongside the percentage of daily recommended values. The MFDS (2019) further recommends that the actual measured values for calories, sodium, sugars, fats, and cholesterol should not exceed 120% of the labeled amounts, whereas values for protein, carbohydrates, dietary fiber, vitamins, and minerals must be at least 80% of the declared values. Nevertheless, a recent report by the Korea Consumer Agency (2022) identified discrepancies between the labeled and actual nutrient contents in some PBMA products. In contrast, certain processed beef products may be exempt from nutrition labeling requirements, particularly if they are classified as items redistributed by meat processing businesses in accordance with existing food labeling and advertising regulations (MFDS, 2024a).

PBMAs are generally developed to replicate the attributes of processed meat products. However, comparative data on their nutritional characteristics, particularly in the patty form, remain limited. Although previous studies have analyzed the nutritional profiles of raw beef and PBMAs (Kim & Jang, 2021; Yang et al., 2023), few have focused on the accuracy of nutritional labeling in commercial patty products.

Therefore, this study aimed to compare the declared nutritional facts with the actual proximate composition of commercial patties made from Hanwoo beef and plant-based proteins, as well as to evaluate their sensory characteristics.

Materials and methods

Sample preparation

Three different types of Hanwoo beef patties (HP) and three varieties of PBMA patties (PP) were purchased from an online market in South Korea and delivered to the laboratory. In this study, HP represents the average of HP-A, HP-B, and HP-C, whereas PP represents the average of PP-A, PP-B, and PP-C. Upon arrival at the laboratory, the samples were mixed using a food mixer and stored at −18 °C or below until analysis. The nutritional information displayed on the product packaging is presented in Table 1, and sample images are shown in Fig. 1.

Proximate composition and total calories

Proximate composition of the samples was evaluated following methods described by the Association of Official Agricultural Chemists (2012). Carbohydrate content was determined by deducting the percentages of moisture, protein, fat, and ash from 100. Total calorie was estimated by applying conversion factors: 4 kcal/g for both protein and carbohydrates, and 9 kcal/g for fat.

Cholesterol content

Cholesterol analysis was performed using a method adapted from the Food Code (MFDS, 2024b) with slight modifications. After combining a 2 g part of the sample with 1 mL of 5α-cholestane and 10 mL of saponification reagent, it was homogenized for 15 s. After incubating at 60 °C for 1 h, the mixture was cooled using cold water, followed by the addition and mixing of 10 mL hexane and 5 mL distilled water. The mixture was centrifuged for 10 min at 2,000 rpm. After being carefully moved to a 20 mL scintillation vial, the top hexane layer (1 mL) was dried in a fume hood. Following drying, the residue was combined with 100 µL of Sylon BFT and 200 µL of pyridine, vortexed gently, and then subjected to gas chromatography (GC) analysis. GC (Agilent 8890 GC, Agilent Technologies, Santa Clara, CA, USA) fitted with an HP-5 capillary column (30 m × 0.32 mm × 0.25 µm, Agilent Technologies, Santa Clara, CA, USA) was used to examine derivatized samples. The carrier gas was

Table 1 The nutritional information listed on the packaging of commercial patty products made with Hanwoo beef and plant-based protein

Samples	Ingredients	Nutrition facts
HP-A	Containing 100% Hanwoo beef and fat	Not shown
HP-B	Hanwoo beef (70%), Hanwoo fat (29%), black pepper powder, smoked flavor powder, salt	Calories (369 kcal), sodium (176 mg), total carbohydrate (5 g), total sugar (0 g), fat (32 g), trans fatty acids (0 g), saturated fatty acids (7 g), cholesterol (76 mg), protein (15 g) per 100 g
HP-C	Hanwoo beef off-cuts (100%)	Not shown
PP-A	Plant-based protein [water, soy protein, particle-concentrated soy protein, apple concentrate, yeast extract], plant-based fat [water, refined palm oil, canola oil, sunflower oil, starch, natural flavors], methylcellulose	Calories (195 kcal), sodium (240 mg), total carbohydrate (11 g), total sugar (Less than 1 g), fat (8 g), trans fatty acids (0 g), saturated fatty acids (2.6 g), cholesterol (0 mg), protein (20 g) per 115 g
PP-B	Water, pea protein, canola oil, coconut oil, rice protein, savory flavor, methylcellulose, potato starch, apple extract, beet extract, maltodextrin, pomegranate extract, salt, potassium chloride, concentrated lemon juice, corn vinegar, carrot powder, sunflower lecithin	Calories (260 kcal), sodium (350 mg), total carbohydrate (5 g), total sugar (0 g), fat (18 g), trans fatty acids (5 g), saturated fatty acids (5 g), cholesterol (0 mg), protein (20 g) per 113 g
PP-C	Soy protein, sauce [mixed soy sauce, sugar, other fructose, pear puree, water, onion puree], canola oil, palm oil, vegan patty sauce, modified starch, other processed products, isolated soy protein, beet	Calories (300 kcal), sodium (530 mg), total carbohydrate (19 g), total sugar (5 g), fat (17 g), trans fatty acids (0 g), saturated fatty acids (7 g), cholesterol (0 mg), protein (17 g) per 100 g

HP, Hanwoo beef patty; PP, plant-based meat analog patty; HP-A; Hanwoo beef patty-A; HP-B; Hanwoo beef patty-B; HP-C; Hanwoo beef patty-C; PP-A, plant-based meat analog patty-A; PP-B, plant-based meat analog patty-B; PP-C, plant-based meat analog patty-C

nitrogen, with a split ratio of 5:1 and a flow rate of 1.5 mL/min. The temperatures of the injector and flame ionization detector were kept at 250 °C and 300 °C, respectively. After being maintained at 190 °C for 2 min, the oven temperature was ramped up to 270 °C at a rate of 40 °C/min and maintained there for a further 25 min.

Mineral contents

To determine the mineral content, 2 g of each sample was ashed in a muffle furnace at 550–600 °C for 12 h in accordance with the Food Code (MFDS, 2024b). Once cooled to ambient temperature, the ashed samples were left to digest overnight in a solution composed of 10 mL of hydrochloric acid and an equal volume of distilled water. An inductively coupled plasma optical emission spectrometer (OPTIMA 7300 DV; PerkinElmer, Shelton, CT, USA) was used to quantify the mineral content of the filtrates after the combination was filtered using filter paper (Whatman No. 6, Whatman, UK).

Sugar contents

The sugar content was determined following the analytical procedure outlined in the Food Code (MFDS, 2024b). For ether layer separation, 25 mL of ether was added to each 5 g sample, followed by vortexing and centrifugation at 783 ×g for 10 min at 4 °C. To ensure full extraction, this process was carried out again. 25 mL of pure water was added after the ether had completely evaporated under a nitrogen gas stream, and the final weight was noted. Samples were heated for 25 min at 85 °C in a water bath in order to extract sugar. The extraction solvent was refilled to return the mixture to its starting weight after it had cooled to room temperature. After passing through a 0.45 μm nylon membrane, the solution was analyzed using HPLC (Agilent Infinity 1260 series, Agilent Technologies, Santa Clara, CA, USA) equipped with a refractive index detector. The following were the chromatographic conditions: A 15 μL volume was injected, with the flow rate maintained at 1.4 mL/min. The mobile phase consisted of acetonitrile and water mixed in a 70:30 (v/v) ratio. Standards for lactose, glucose, sucrose, fructose, and maltose were obtained from Sigma-Aldrich (St. Louis, MO, USA).

Fatty acid composition

A technique modified slightly from the Lee et al. (2023) methodology was used to assess the fatty acid makeup of the samples. Each 5 g sample was mixed with 50 μL of butylated hydroxytoluene and 30 mL of Folch reagent (chloroform: methanol, 2:1, v/v), followed by two rounds of homogenization. The homogenized sample was kept at ambient temperature for 3 h, shaking every 30 min, and then filtered. To cause phase separation, the filtrate was combined with 9 mL of 0.88% NaCl solution, agitated for 2 min, and left to stand for 24 h. Ten milliliters of the lower chloroform phase were collected for lipid extraction and evaporated under nitrogen gas to reduce fatty acid oxidation following phase separation. Methylation reagent (1 mL) was applied after the separated lipids had been redissolved in 2mL of chloroform. The sample was maintained at 60 °C for 40 min. Afterward, it was cooled using cold water, followed

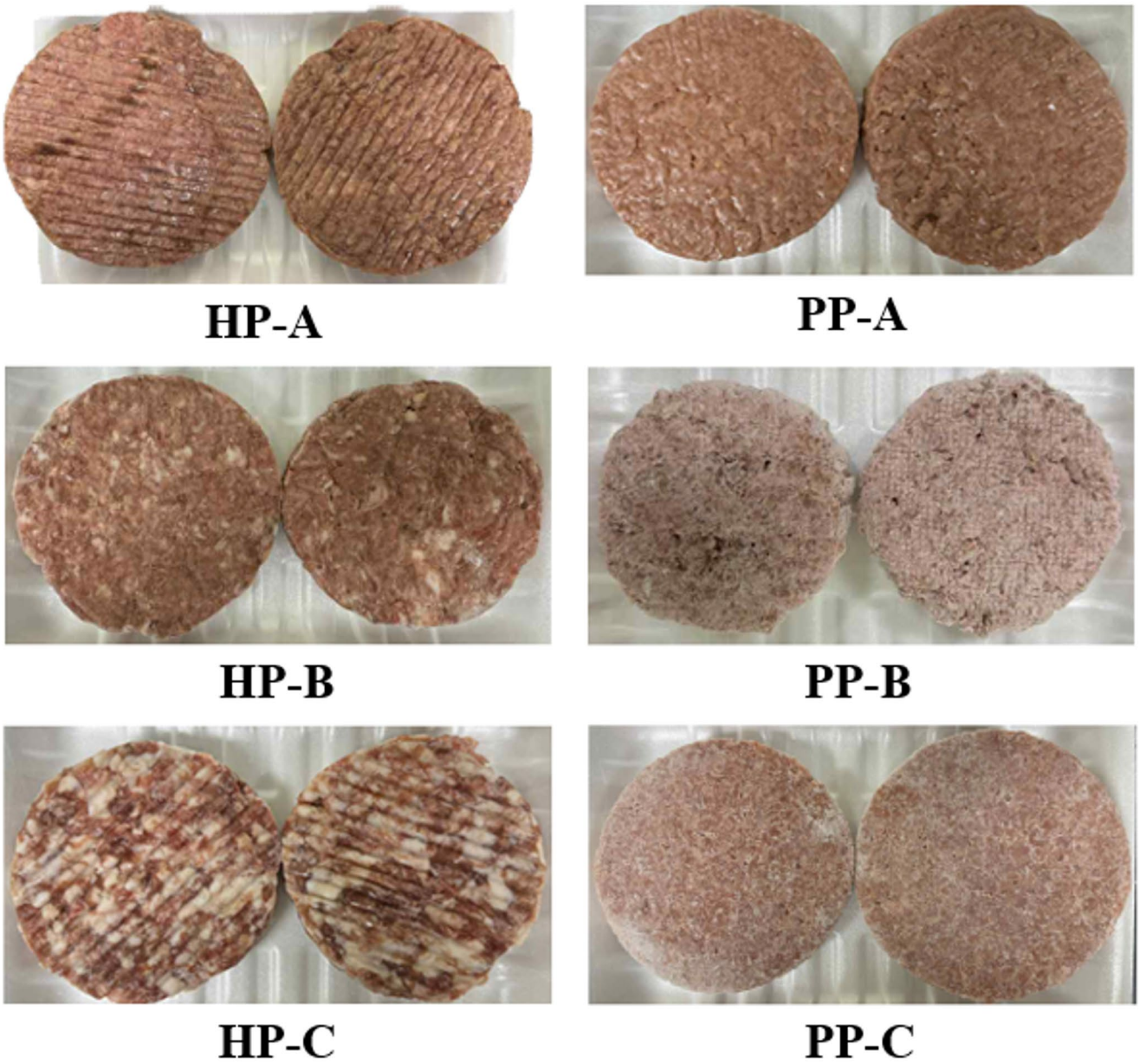


Fig. 1 Images of commercial patties made from Hanwoo beef and plant-based protein. HP, Hanwoo beef patty; PP, plant-based meat analog patty

by the addition of hexane (3 mL) and distilled water (8 mL). After 5 min of centrifuging the mixture at 2,000 rpm, the top hexane layer was carefully removed for further fatty acid analysis. A gas chromatography-mass spectrometry (7890 B gas chromatography and 5977 B mass spectrometry, Agilent Technologies, Santa Clara, CA, USA) fitted with a DB-WAX capillary column (Agilent Technologies, Santa Clara, CA, USA) was used to analyze fatty acids. Helium served as the carrier gas in the GC system at a constant flow rate of 1.0 mL/min. The oven was first set to 50 °C for 1 min, then heated to 200 °C at a rate of 25 °C/min. After that, the temperature gradually rose to 230 °C at 3 °C/min and held steady at 230 °C for 18 min. A temperature of 250 °C was chosen for the intake. The ion source was maintained at 230 °C and the quadrupole at 150 °C. The mass spectrometer operated using electron impact ionization at 70 eV, and mass spectra were recorded in scan mode over a range of 30 to 450 m/z. Fatty acids were identified and quantified using a FAME mix standard (CRM18920; Supelco™, Millipore Sigma Supelco, Bellefonte, USA).

Amino acid composition contents

The amino acid profiles were determined according to the method described by Joo et al. (2022). Each sample, weighing around 1 g, was homogenized at 12,000 rpm for 15 s.

The homogenized sample was transferred to a glass container, and 6 M HCl was added. Nitrogen gas was then introduced, and the mixture was subjected to hydrolysis at 110 °C for 24 h. After hydrolysis, the solution was transferred to a 50 mL volumetric flask and brought to volume with sodium citrate buffer (pH 2.2) using a calibrated measuring tube. The resulting solution was filtered through a 0.45 µm membrane and transferred into an autosampler vial. An amino acid analyzer (SYKAS433, Sykam GmbH, Eresing, Germany) was used to determine the content of amino acids.

Sensory evaluation

A total of 125 panelists, aged 20 to 50, from Kangwon National University and Chung-Ang University participated in the sensory evaluation. The samples were pan-fried on a surface heated to 180 °C and cooked until they reached an internal temperature of 72±2 °C. After assessing each sample, the panelists washed their mouths with water after cutting each patty into 2×2×1 cm pieces. Sensory attributes, including appearance, color, off-flavor, taste, flavor, juiciness, tenderness, and overall acceptability, were evaluated using a nine-point hedonic scale. The scores for appearance, color, taste, flavor, and overall acceptability ranged from 1 (very bad) to 9 (very good). Off-flavor was assessed on a scale from 1 (very weak) to 9 (very strong), whereas juiciness and tenderness were rated from 1 (very dry or very hard) to 9 (very juicy or very tender). The sensory evaluation protocol was approved by the Institutional Review Board (IRB) of Kangwon National University (KWNUIRB-2023-11-004-002).

Statistical analysis

Data in tables are presented as means±standard error of the mean (SEM), while data in figures are presented as means±standard deviation. Statistical analyses were conducted using SAS software (version 9.4; SAS Institute, Cary, NC, USA) with one-way analysis of variance (ANOVA) followed by Tukey's test. Differences among means were considered statistically significant at $p<0.05$. Multivariate analysis was performed using partial least squares-discriminant analysis (PLS-DA) along with variable importance in projection (VIP) scores. Log-transformed and auto-scaled data were analyzed using MetaboAnalyst 6.0 (https://www.metaboanalyst.ca).

Results and discussion

Proximate composition and total calories

The proximate composition and total calorie content of HP and PP are presented in (Fig. 2). Protein content is an important macronutrient when evaluating meat products and PBMAs (Yang et al., 2023). Textured vegetable protein (TVP), with a fibrous structure similar to ground meat, serves as the protein source in PBMAs (Kyriakopoulou et al., 2021). The study revealed that HP exhibited a significantly higher crude protein content compared to PP ($p<0.05$). These findings are consistent with those of Bakhsh et al. (2021), who reported that beef patties contained more protein than PP. A significant increase in crude lipid content was also observed in HP compared to PP, resulting in a higher total calorie content for HP ($p<0.05$). Fat is an important component in processed meat products as it enhances juiciness, tenderness, and overall flavor. Similarly, PBMAs require fat to mimic these sensory characteristics; however, excessive fat intake can lead to health issues (Jiménez-Colmenero et al., 2001; Kyriakopoulou et al., 2021). Carbohydrates, along with fats, are commonly included in PBMAs to reduce fat intake and lower production costs (Owusu-Ansah et al., 2022; Kyriakopoulou et al., 2021). In this study, no carbohydrates were detected in the HP group, whereas the PP group contained 9.68% carbohydrates. According to the nutritional information provided, the PP group included a variety of carbohydrate ingredients (Table 1). However, Xie et al. (2022b) reported that the protein digestibility in PBMAs was lower than that in real meat, which they attributed to the high viscosity of the digesta caused by starch. In meat and PBMAs, the interactions between nutrients based on their content and their impact on degradation require further investigation.

A comparison between the nutritional values stated on product labels and those obtained from actual measurements revealed significant discrepancies. As shown in Table S1, the labeled carbohydrate content of HP-B was 5 g per 100 g; however, no carbohydrates were detected during the analysis. For PP-A, the deviation between the labeled and measured values was 68.00% for fat and 165.63% for protein. Similarly, PP-C exhibited a 68.89% error in carbohydrate labeling. These discrepancies suggest the need for stricter regulations and quality controls regarding the labeling of PBMAs and meat products (MFDS, 2019). Such inconsistencies between declared and actual nutritional values could undermine consumer trust, highlighting the need for a more robust quality assurance system within the food industry. Therefore, further in-depth research is warranted to establish standardized analytical protocols and strengthen

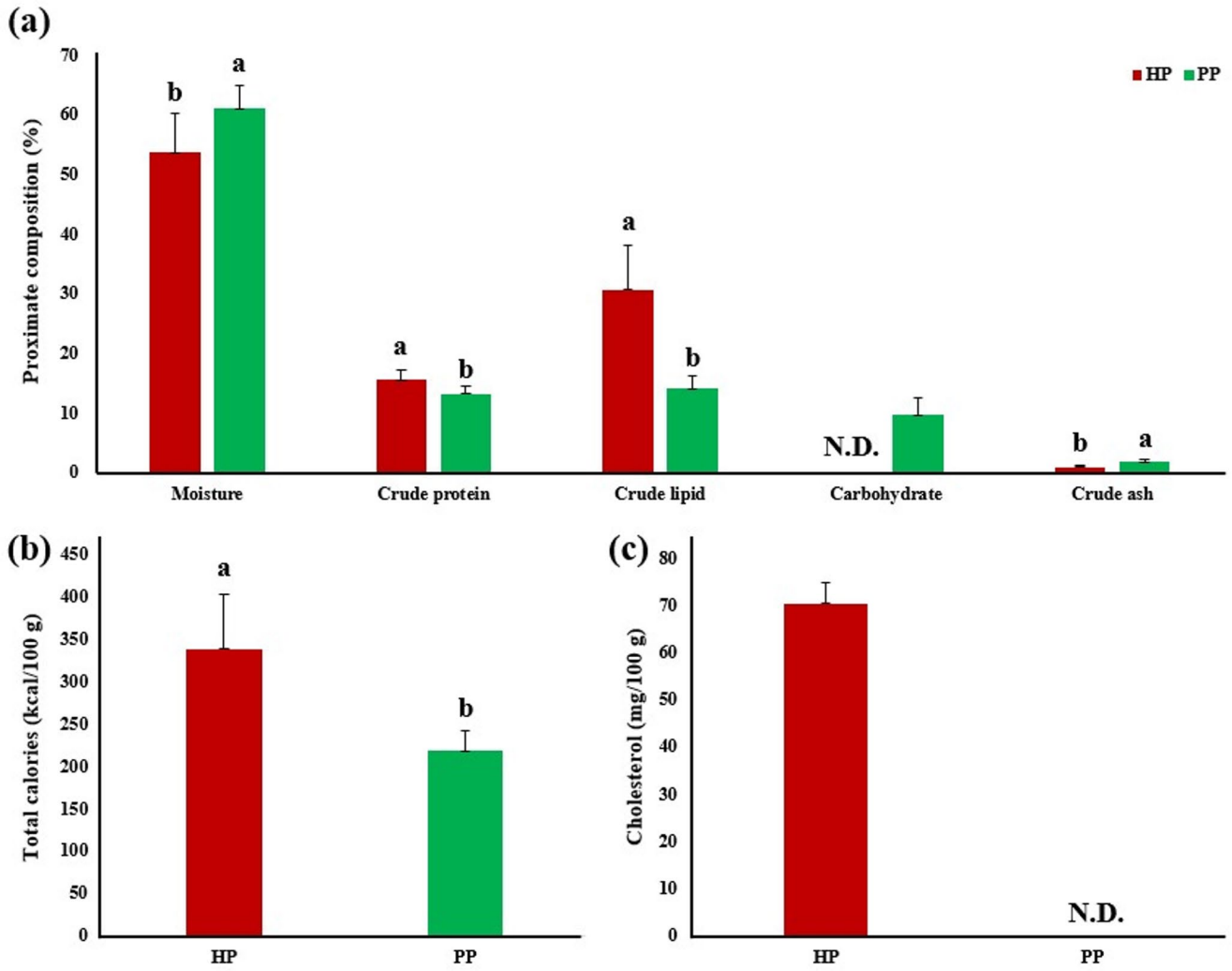


Fig. 2 Proximate composition, total calories, and cholesterol content of the commercial patties made with Hanwoo beef and plant-based protein. Proximate composition (**a**), total calories (**b**), and cholesterol content (**c**) from Hanwoo beef patty and plant-based meat analog patty.

a, b Means between HP and PP with different superscript differ significantly at $p < 0.05$. HP, Hanwoo beef patty; PP, plant-based meat analog patty; N.D., not detected

oversight mechanisms to improve labeling accuracy and enhance product credibility.

Cholesterol content

Cholesterol is essential for maintaining physiological functions; however, excessive intake is associated with an increased risk of coronary heart disease and is therefore considered an important factor influencing food choices (Cortes et al., 2014; Sujiwo et al., 2017). The cholesterol content in the HP group was 70.46 mg/100 g (Fig. 2c), whereas no cholesterol was detected in the PP group. According to the Korean Ministry of Food and Drug Safety (MFDS, 2019) labeling standards, the suggested maximum daily intake of cholesterol is 300 mg. Therefore, the cholesterol content in the HP group in this study was below the recommended level. Several studies worldwide have reported similar findings regarding cholesterol levels in PBMAs. Yang et al. (2023) found that the cholesterol content in various beef cuts, including tenderloin, eye round, flank, and shoulder, ranged from 48.40 to 63.47 mg/100 g, while PBMAs contained between 0 and 6.20 mg/100 g. These findings align with the results of this study. The observed differences are likely due to the distinct ingredients used in these products. In animal products, sterols mainly exist as cholesterol within cell membranes (Schade et al., 2020). In contrast, plant sterols are primarily present as campesterol, stigmasterol, and sitosterol (Sonawane et al., 2016). Unlike cholesterol, plant sterols are typically transported back into the intestine via the ATP-binding cassette transporters ABCG5/ABCG8 and are excreted in feces (Schade et al., 2020). These results suggest PP, being free of cholesterol, may

Table 2 Mineral contents of commercial patties made with Hanwoo beef and plant-based proteins

Minerals (mg/100 g)	HP	PP	SEM
Ca	34.64	55.04	11.898
Fe	1.54[b]	1.96[a]	0.110
K	195.12[b]	290.91[a]	21.885
Mg	18.01[b]	42.01[a]	4.964
Na	131.15[b]	319.75[a]	34.585
Zn	3.55[a]	0.93[b]	0.236
P	191.77	186.43	14.860
Cu	0.83	1.08	0.192
Al	N.D.	0.31	-

HP, Hanwoo beef patty; PP, plant-based meat analog patty; N.D., Not detected; SEM,Standard error of the mean

[a, b]Means within a row with different superscript differ significantly at $p < 0.05$

Table 3 Sugar contents of commercial patties made with Hanwoo beef and plant-based protein

Sugar (g/100 g)	HP	PP	SEM
Fructose	0.02[b]	0.65[a]	0.181
Glucose	0.10[b]	0.44[a]	0.096
Sucrose	0.03[b]	1.29[a]	0.413
Maltose	0.01	0.01	0.006
Lactose	N.D.	N.D.	-
Total	0.17[b]	2.39[a]	0.687

HP, Hanwoo beef patty; PP, plant-based meat analog patty; N.D., Not detected; SEM, Standard error of the meanaaa

[a, b]Means within a row with different superscript differ significantly at $p < 0.05$

offer advantages for consumers seeking to manage their cholesterol intake. However, the cholesterol content of HP also remained within the recommended daily intake levels, and cholesterol is an essential component that performs various physiological functions in the human body (Cortes et al., 2014). Therefore, both product types should be appropriately incorporated into a balanced diet.

Mineral contents

Table 2 presents the mineral contents of HP and PP. Minerals are essential micronutrients that contribute significantly to human health by supporting cellular activities, neuromodulation, and various biochemical and physiological processes (Falowo, 2021). Among these, zinc and iron are particularly abundant in beef (Cabrera & Saadoun, 2014; Kim & Jang, 2021). Zinc is crucial for cell growth, immune function, bone development, and brain health, with deficiencies potentially leading to conditions such as acrodermatitis, cirrhosis, and diabetes (Falowo, 2021). The study found that HP had significantly higher zinc content than PP ($p<0.05$). Iron, an essential mineral, plays a vital role in supporting healthy growth and development, especially during childhood, and its deficiency can result in multiple health problems (Jang et al., 2019). PP, however, exhibited significantly higher iron content than HP. Furthermore, potassium (K) and magnesium (Mg) levels were significantly higher in PP than in HP, while calcium (Ca), phosphorus (P), and copper (Cu) were not significantly different between the two groups. These results suggest that the incorporation of nutritional enhancers by manufacturers may allow PBMAs to achieve mineral profiles comparable to those of real meat (Yang et al., 2023). These results align with earlier research that compared the mineral composition of conventional meat and PBMAs (Yang et al., 2023; Yea et al., 2023). However, despite the similar mineral contents in HP and PP, the bioavailability of certain minerals (e.g., iron and zinc) may be reduced when consumed from plant-based sources. Hence, additional studies are needed to gain a clearer understanding of mineral bioavailability in PBMAs (Yea et al., 2023).

Excessive sodium intake has been linked to various diseases; therefore, there is a growing trend in the food industry to develop processed meat products aimed at sodium reduction (Inguglia et al., 2017). In this study, PP exhibited a significantly higher sodium content than HP ($p<0.05$). These findings align with those of Yang et al. (2023), who reported that the sodium levels in commercial PBMAs exceeded those found in beef. Excessive salt intake may lead to elevated blood pressure and a higher risk of heart-related diseases. According to the food labeling standards set by the MFDS (2019), the recommended daily intake of sodium is 2,000 mg. Although the sodium content in PP remained below the recommended daily limit, reducing sodium levels would still be beneficial, aligning with current nutritional trends promoting health (Kyriakopoulou et al., 2021). When comparing the nutritional information on the packaging with the actual measured values, the sodium content in HP-B deviated from the labeled standards by 136.02% (Table S1).

Sugar contents

The sugar contents of HP and PP are presented in Table 3. Sweeteners are added to foods primarily to enhance palatability and may include nutritive sweeteners such as sucrose, fructose, and glucose, as well as non-nutritive artificial alternatives (Carocho et al., 2014). Reducing sugars are commonly incorporated into PBMAs to promote Maillard reactions, which contribute to the development of meat-like aromas and flavor profiles (Kyriakopoulou et al., 2021). Sun et al. (2023) demonstrated that the addition of reducing sugars such as xylose, ribose, glucose, fructose, and galactose to soybean meal hydrolysates effectively induces the Maillard reaction. In the present study, PP samples exhibited

significantly higher concentrations of fructose and glucose compared to HP samples.

Sucrose, the most widely used sweetener and global reference standard for sweetness (Carocho et al., 2017), was present at significantly higher levels in the PP group than in the HP group ($p < 0.05$). Consuming too much sugar has been linked to a wide range of negative health effects, such as cardiovascular disease, type 2 diabetes, metabolic syndrome, high triglyceride levels, insulin resistance, obesity (including in children), high blood pressure, and certain cancers like breast and colorectal cancer (Carocho et al., 2017). According to the food labeling standards set by the MFDS (2019) in Korea, the recommended daily intake of total sugar is 100 g. Although the total sugar content in PP was significantly higher than that in HP, all patty products analyzed in this study remained below the recommended daily limit based on a 100 g portion size.

A comparison of the nutritional information declared on packaging with the analytically determined values revealed that the total sugar content of PP-C deviated substantially from food labeling standards (MFDS, 2019). Specifically, the discrepancy between the labeled and actual total sugar contents reached 125.60%, indicating noncompliance with regulatory thresholds (Table S1).

Table 4 Fatty acid composition of commercial patties made with Hanwoo beef and plant-based protein

Fatty acid	HP	PP	SEM
C8:0 (Caprylic acid)	0.19[b]	4.85[a]	0.035
C10:0 (Capric acid)	0.12[b]	3.44[a]	0.022
C12:0 (Lauric acid)	1.76[b]	9.78[a]	0.065
C14:0 (Myristic acid)	2.19[b]	6.97[a]	0.052
C16:0 (Palmitic acid)	26.59[a]	8.13[b]	0.150
C16:1 (Palmitoleic acid)	2.50[a]	0.33[b]	0.022
C18:0 (Stearic acid)	16.29[a]	6.49[b]	0.192
C18:1n9 (Oleic acid)	39.02[a]	31.55[b]	0.303
C18:1n7 (Vaccenic Acid)	1.32	N.D.	-
C18:2n6 (Linoleic acid)	5.94[b]	17.01[a]	0.122
C18:3n3 (α-Linolenic acid)	3.01[b]	8.03[a]	0.051
C20:0 (Arachidic acid)	0.33[b]	1.06[a]	0.004
C20:1n9 (Eicosenoic acid)	0.65[b]	1.75[a]	0.011
C20:3n3 (Eicosatrienoic acid)	0.06	N.D.	-
C20:4n6 (Arachidonic acid)	0.04	N.D.	-
C22:0 (Behenic acid)	N.D.	0.62	-
SFA	47.46[a]	41.33[b]	0.207
UFA	52.54[b]	58.67[a]	0.207
MUFA	43.50[a]	33.63[b]	0.304
PUFA	9.04[b]	25.04[a]	0.147
MUFA/SFA	0.92[a]	0.81[b]	0.011
PUFA/SFA	0.19[b]	0.61[a]	0.003

HP, Hanwoo beef patty; PP, plant-based meat analog patty; N.D., Not detected; SEM, Standard error of the mean

[a, b]Means within a row with different superscript differ significantly at $p < 0.05$

Fatty acid composition

The fatty acid compositions of HP and PP are listed in Table 4. In this study, the predominant fatty acids found in HP were oleic, palmitic, and stearic acids. The results align with those observed by Kim and Jang (2021), who examined the fatty acid profiles of 1+grade Hanwoo loin and round cuts. In contrast, the main fatty acids present in PP were oleic and linoleic acids. According to Yang et al. (2023), the type and proportion of oils used significantly affect the fatty acid content of PBMAs. Common oils used in PBMAs include coconut, sunflower seed, and canola oils. Coconut oil primarily contains lauric, myristic, palmitic, and oleic acids, while sunflower seed and canola oils predominantly contain oleic and linolenic acids. As outlined in the ingredient lists in Table 1, PP-A was made with palm oil, canola oil, and sunflower oil; PP-B with canola oil and coconut oil; and PP-C with canola oil and palm oil.

Meat is a major contributor of saturated fatty acids (SFAs), which are associated with a higher likelihood of developing diabetes and cardiovascular conditions (Geiker et al., 2021). In this study, the total SFAs in the HP group were significantly higher than those in the PP group. However, oleic acid and monounsaturated fatty acids (MUFAs), which play a key role in the flavor and organoleptic properties of meat (Kim et al., 2019), were present at significantly higher levels in HP than in PP ($p < 0.05$). The elevated oleic acid levels in HP may be attributed to the fatty tissues of cattle, particularly the high oleic acid content in Hanwoo adipose tissue (Kim & Jang, 2021).

The ratio of polyunsaturated to saturated fatty acids (PUFA/SFA) is commonly used as an indicator of fat quality in meat, with recommended values greater than 0.4 or 0.5 (Kim et al., 2019). In this study, the PUFA/SFA ratio exceeded the recommended value in PP but was lower than that in HP.

Vaccenic acid, a trans fatty acid, was identified in the samples. This predominant trans-fatty acid is formed through microbial hydrogenation of unsaturated fatty acids in the rumen of animals that chew cud (Phillips et al., 2010). In the HP-B sample, trans fat was labeled as 0 g, while vaccenic acid was detected at a level of 1.34%. Additionally, vaccenic acid was present in the HP-A and HP-C samples (Table S1). Since 2003, the U.S. Food and Drug Administration has required the inclusion of trans fatty acids on nutrition labels. Conjugated linoleic acid is not subject to mandatory labeling, and vaccenic acid, in contrast to industrial trans fats, has not been associated with negative effects on cardiovascular health. Despite this, vaccenic acid continues to be classified alongside other trans fats in labeling regulations. As a result, certain studies have proposed that

vaccenic acid present in foods of animal origin should be measured and reported independently (Phillips et al., 2010).

Amino acid composition

The amino acid compositions of HP and PP are presented in Fig. 3. Meat proteins remain a vital component of human nutrition and have contributed greatly to the evolutionary development of humans (Bakhsh et al., 2021). Protein quality and nutritional value are commonly evaluated based on amino acid composition (Yang et al., 2023). In this study, the essential amino acids, except for lysine, demonstrated the potential of PP to mimic HP. However, plant-based proteins often have a limited number of amino acids. Methionine is typically the limiting amino acid in legume-based proteins, while lysine and threonine are the main limiting amino acids in cereal proteins. Combining legume and cereal proteins can improve the amino acid balance, yet a study by Yang et al. (2023) reported that several commercially available PBMA products still lacked sufficient lysine, a finding that is consistent with the results of the present study.

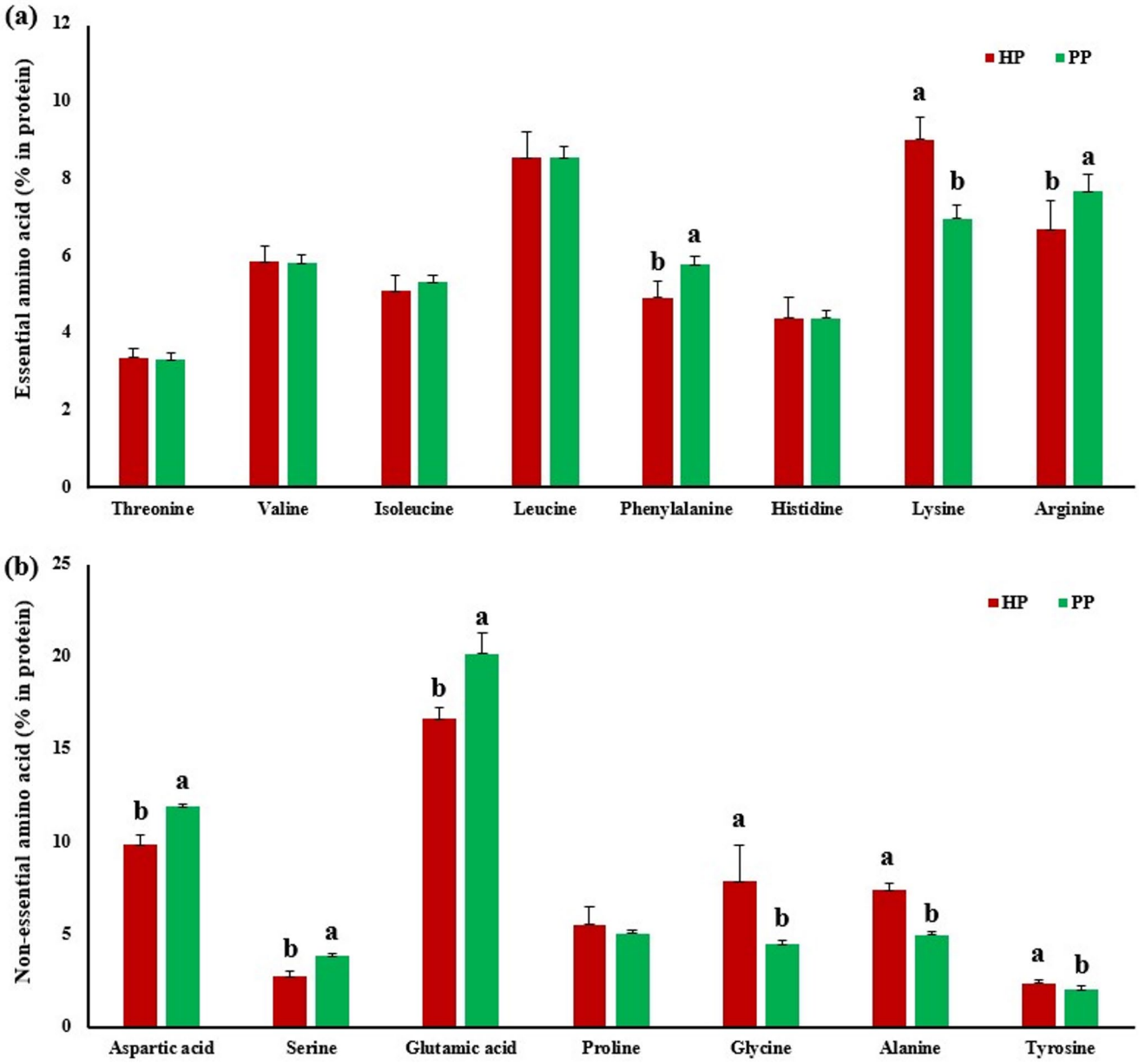


Fig. 3 Amino acid composition of the commercial patties made with Hanwoo beef and plant-based protein. Essential amino acid (**a**) and non-essential amino acid (**b**) from Hanwoo beef patty and plant-based meat analog patty. a, b Means between HP and PP with different superscript differ significantly at $p < 0.05$. HP, Hanwoo beef patty; PP, plant-based meat analog patty

The overall taste of amino acids comprises fundamental flavors such as sourness, saltiness, sweetness, bitterness, and umami. The amino acid composition of meat plays a significant role in shaping these taste sensations. Since the umami flavor is crucial to the taste of meat, it is essential to replicate the key amino acids, such as glutamic acid and aspartic acid, to make effective meat substitutes (Joo et al., 2022). In the present study, aspartic and glutamic acid levels were significantly higher in PP than in HP. According to Samard and Ryu (2019), TVP contained a higher level of glutamic acid compared to beef. Yang et al. (2023) reported that commercial PBMAs generally contain higher levels of glutamic acid than beef, although the aspartic acid content varies depending on the product.

Multivariate analysis of nutritional profiles

PLS-DA and VIP scores were evaluated to verify group classification and identify the biomarkers contributing to the differences between groups (Shin et al., 2024). PLS-DA is a statistical technique commonly used in biostatistics, medical research, and food sciences. This method is particularly effective for analyzing datasets with strongly correlated predictors, as it produces reliable models even when there is substantial variability or interdependence among the input variables (Oh et al., 2023).

In this study, components 1 and 2 accounted for 74.8% of the overall variation in nutrient composition, suggesting a well-fitting model ($R^2 = 0.999$, $Q^2 = 0.998$) (Fig. 4a). When evaluated along Component 1, HP was located in the negative region, while PP was positioned in the positive region. Component 1 contributed more significantly to the model than Component 2, suggesting greater discriminative power. These results indicate that HP and PP exhibit distinct nutritional profiles.

The VIP method was used to evaluate the effect of each nutrient on group differentiation. Variables with VIP scores greater than 1 were considered significant contributors to group separation (Oh et al., 2023). In this study, the VIP scores were evaluated based on Component 1, which explained the highest proportion of total variance and showed the strongest discriminative power. Among these, arachidic acid (C20:0) was the most influential variable in distinguishing the clusters (Fig. 4b). In plasma fatty acid composition, arachidic acid (C20:0) has been reported to have a negative association with gestational diabetes mellitus, suggesting its potential to reduce the risk of gestational diabetes mellitus (Sun et al., 2022). In the study, the arachidic acid (C20:0) was significantly higher in the PP group than in the HP group (Table 4).

Sensory characteristics

The results of the sensory evaluation for the HP and PP groups are shown in Fig. 5. In the development of PBMAs, the focus has shifted toward producing sustainable products that replicate not only the nutritional similarity of meat but also all its physical sensations, including texture,

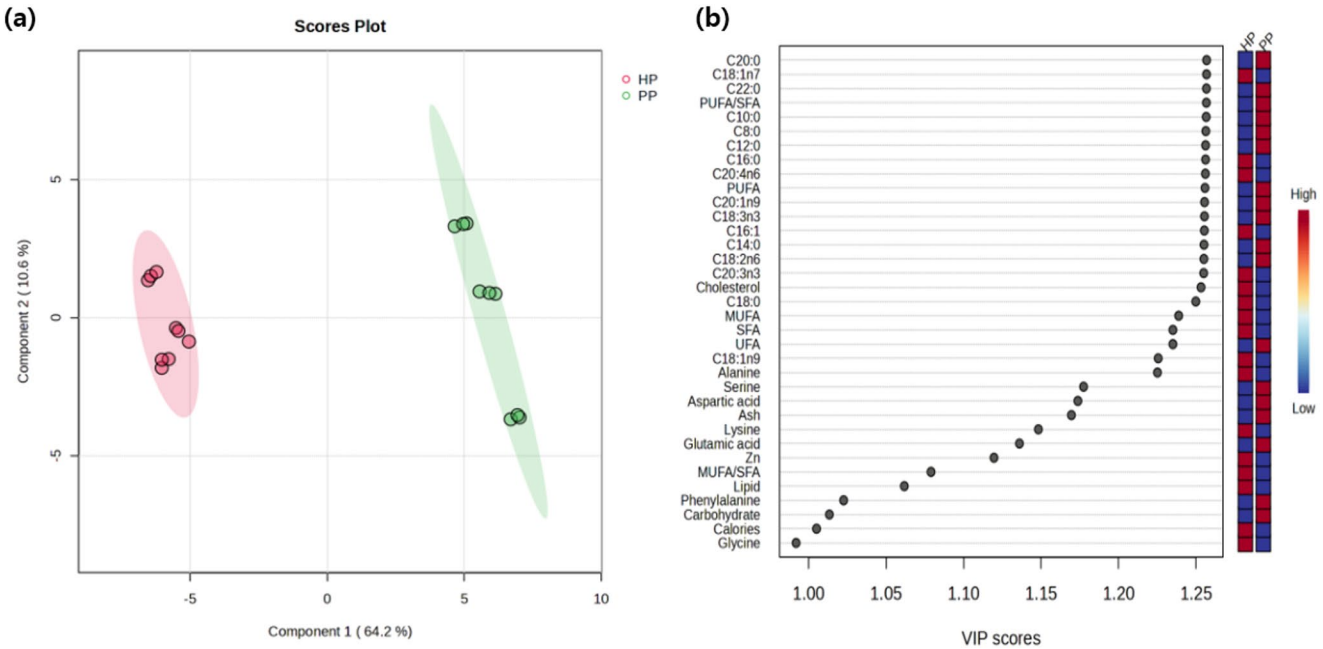


Fig. 4 Multivariate analysis of nutritional profiles of the commercial patties made with Hanwoo beef and plant-based protein. Partial least squares-discriminant analysis (PLS-DA) (**a**), and its variable importance in projection scores (VIP scores) (**b**) from Hanwoo beef patty and plant-based meat analog patty. HP, Hanwoo beef patty; PP, plant-based meat analog patty

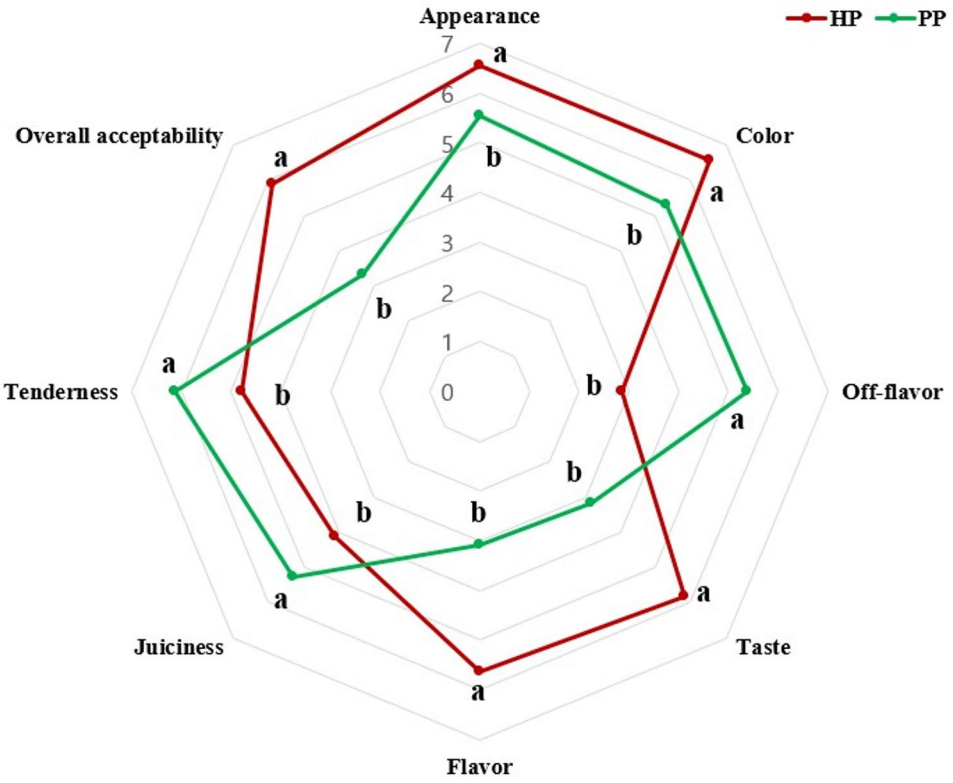


Fig. 5 Radar charts of the sensory characteristics of the commercial patties made with Hanwoo beef and plant-based protein. a, b Means between HP and PP with different superscript differ significantly at $p<0.05$. HP, Hanwoo beef patty; PP, plant-based meat analog patty. Appearance, color, taste, flavor, overall acceptability (1 = very bad, 9 = very good), off-flavor (1 = very weak, 9 = very strong), juiciness (1 = very dry, 9 = very juicy), tenderness (1 = very hard, 9 = very tender)

appearance, smell, and taste (Kyriakopoulou et al., 2021). The visual appearance of meat products plays a crucial role in determining the consumer's purchasing decision (Kim & Jang, 2021). In the study, HP received significantly higher scores for appearance compared to the PP group ($p<0.05$). These results may indicate that there is a difference in the appearance between the HP and PP groups.

In animal meat, myoglobin is responsible for its color, producing the light and bright red appearance of fresh meat. HP received significantly higher scores for color compared to the PP group ($p<0.05$). During cooking, myoglobin is denatured by heat and changes to a brown color (Ryu et al., 2023). PBMAs need to be designed to exhibit color changes during cooking similar to those observed in meat (Kyriakopoulou et al., 2021).

A notable finding from this study relates to taste- and flavor-associated attributes. HP achieved higher scores for taste and flavor than PP, while PP showed significantly higher off-flavor scores than HP ($p<0.05$). According to Table S1, all HP products (HP-A, HP-B, and HP-C) exhibited significantly higher taste and flavor scores and significantly lower off-flavor scores than all PP products (PP-A, PP-B, and PP-C). These differences can likely be attributed to variations in flavor-related compounds between HP and PP. In PBMAs, off-flavors such as beany flavor, bitterness, aftertaste, and astringency have been frequently reported, which are known to be attributed to intrinsic constituents of the plant-based ingredients (Wang et al., 2022). Also, the presence of saponins and isoflavones in soy protein, the primary ingredient in PBMAs, has been reported to contribute to bitter and astringent tastes, which may negatively impact sensory quality (Bakhsh et al., 2021). To mitigate these issues, various additives are incorporated into PBMAs (Kyriakopoulou et al., 2021). The contents of sodium, which can act as a taste enhancer (Kyriakopoulou et al., 2021), and total sugars, which can improve the palatability of foods (Carocho et al., 2014), were higher in the PP group than in the HP group (Tables 2 and 3). Mennella et al. (2014) reported that both children and adults showed a significant positive correlation between their preferences for salty and sweet tastes in relation to the salt concentration of broth and the sucrose concentration of water. Additionally, Seol et al. (2015) reported that oleic acid enhanced the palatability of beef, while palmitic acid and stearic acid positively influenced sensory properties. In the present study, the concentrations of oleic, palmitic, and stearic acids were significantly lower in the PP group than in the HP group (Table 4). In this study, these fatty acids had VIP scores greater than 1 and were identified as biomarkers distinguishing between the HP and PP groups (Fig. 4b).

In terms of texture, the juiciness scores of the PP group were significantly higher than those of the HP group. This may be attributed to reduced moisture loss during cooking, likely resulting from the gelation of carbohydrate-based materials or carbohydrate–protein complexes in PBMAs (Bakhsh et al., 2021; Nath et al., 2022). In addition, the

tenderness scores of the PP group were significantly higher than those of the HP group. Soy- and legume-based ingredients, as well as carbohydrate materials, are often used in PBMAs as binding or texturizing agents (Kyriakopoulou et al., 2021). Various soy, legume, and carbohydrate ingredients were also included in the formulation of the PP sample used in this study (Table 1). Nevertheless, the difference in tenderness between HP and PP is interpreted as being due to the inherent limitations of PBMAs manufacturing process, which makes it difficult to fully replicate the structural characteristics of real meat products (Ishaq et al., 2022).

Consequently, the overall acceptability was significantly higher in the HP group than in the PP group. This result may be closely related to the sensory differences observed across multiple attributes. In the study, HP exhibited superior scores for appearance, color, taste, and flavor while showing significantly lower off-flavor and tenderness scores compared with PP. Previous studies have reported that taste/flavor, texture, appearance, color, and odor are the most important intrinsic attributes influencing consumer acceptability of meat products (Cardona et al., 2023). The PP group received higher scores for juiciness; however, this advantage did not fully compensate for its lower appearance and flavor characteristics. Therefore, the overall preference for HP is interpreted to stem from its superior appearance and flavor characteristics.

Conclusion

This study thoroughly compared the nutritional compositions and sensory characteristics of HP and PP. HP demonstrated significantly higher levels of protein, fat, total calories, zinc, oleic acid, saturated fatty acids, monounsaturated fatty acids, and lysine, as well as superior performance in sensory attributes such as appearance, color, taste, flavor, and overall acceptability. In contrast, the PP group contained no detectable cholesterol, demonstrated a significantly higher PUFA/SFA ratio, and exhibited higher levels of certain minerals, sugars, and umami-contributing amino acids, such as glutamic acid and aspartic acid. However, in the sensory evaluations, the PP group received significantly higher scores for off-flavors. Discrepancies between labeled and actual nutritional values were observed in several HP and PP products. In HP-B, inconsistencies were found in sodium, carbohydrates, and trans fatty acids; in PP-A, differences were found in fat and protein; and in PP-C, inconsistencies were observed in carbohydrates and total sugars. These findings highlight the need for more rigorous quality control measures. Future studies should focus on enhancing the sensory attributes and improving nutrient bioavailability in PBMAs, as well as refining the accuracy of nutritional labeling to meet regulatory standards. Overall, the results of this study offer valuable insights into the nutritional profiles of HP and PP, contributing to the reliability of the global market and supporting the promotion of sustainable food consumption.

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Author contributions A. Jang, D. Kim, and S. Oh conceptualized and designed the study. D. Kim, S. Oh, and D.Y. Lee curated the data. S. Oh, D.Y. Lee, D. Kim, and Y. Jung conducted the formal analysis. The methodology was developed by A. Jang, D. Kim, and S.J. Hur. Software analysis was performed by S. Oh and D.Y. Lee. A. Jang and S.J. Hur validated the findings. The investigation was carried out by A. Jang, D. Kim, and S. Oh. The original draft of the manuscript was written by A. Jang, D. Kim, and S. Oh, and the manuscript was reviewed and edited by A. Jang, S. Oh, D. Kim, and S.J.Hur.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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