Versi Online: http://journal.ipb.ac.id/index.php/jtip
https://doi.org/10.6066/jtip.2025.36.2.167
Hasil Penelitian

Jurnal Teknologi dan Industri Pangan
Vol. 36(2): 167-180 Th. 2025 ISSN: 1979-7788
Terakreditasi Kemendikbudristek: 164/E/KPT/2021

Physicochemical and Sensory Properties of Plant-Based Milk Alternative Produced from Pigeon Pea and Soybean

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Received December 9th 2024 / Revised April 28th 2025 / Accepted June 6th 2025

ABSTRACT

The popularity of plant-based milk alternatives (PBMA) has been growing due to environmental concerns and health benefits. This study aimed to develop and evaluate a novel PBMA formulation combining pigeon pea and soybean at three different ratios (40:60, 50:50, and 60:40), focusing on their physicochemical characteristics, sensory properties, and antioxidant activity. In this study, significant differences (p<0.05) were found in the physicochemical properties of the samples, while sensory acceptability showed no significant differences (p>0.05). Increasing the proportion of pigeon pea resulted in a lower level of ash, protein, fat, color, viscosity, and pH, while the content of moisture, carbohydrate, and soluble solids increased. The formulations contained 91.84–92.39% moisture; 0.09–0.12% ash; 0.80–1.48% protein; 0.81–1.04% crude fat; and 5.52–5.91% carbohydrate. Additionally, they had lightness values of 59.74–68.57; greenness/redness values of -0.53–0.68; yellowness values of 6.60–8.13; viscosities of 11.42–12.50 cP; soluble solids of 6.00–9.00 °Brix; and pH of 6.69–6.72. The sensory evaluation ranged from "neither like nor dislike" to "slightly like" (5.24–5.97 on a 9-point scale), indicating moderate acceptability across all formulations. Despite being acknowledged as having a beany aroma, the panelists identified sweet and creamy notes with low bitterness in the sample, contributing to a relatively pleasant flavor. Furthermore, the 50:50 pigeon pea-to-soybean formulation contained daidzein as the predominant isoflavone and demonstrated high antioxidant activity (91.90% DPPH inhibition). These findings suggest that the developed PBMA is a promising functional beverage with good nutritional and sensory qualities.

Keywords: antioxidant activity, isoflavone content, pigeon pea, plant-based milk, soybean

INTRODUCTION

Plant-based milk alternatives (PBMAs) are aqueous extracts from various plant materials, such as legumes, nuts, seeds, cereals, and pseudo-cereals, that resemble cow's milk in appearance and consistency (Kasapidou *et al.,* 2023; Romulo, 2022). These beverages are typically produced by soaking the raw plant source, blending it with water, and filtering the mixture to separate the liquid phase from solid residues. Further processing methods, such as homogenization and thermal treatment, are commonly applied to improve suspension stability and microbial safety (Kasapidou *et al.,* 2023). PBMAs are generally classified into five categories: (a) cereal-based (e.g., oat, rice, corn), (b) legume-based (e.g., soy, peanut, cowpea), (c) nut-based (e.g., almond, hazelnut, coconut), (d) seed-based (e.g., sesame, flax, sunflower), and (e) pseudocereal-based (e.g., quinoa, amaranth, teff) (Romulo, 2022).

The nutritional composition of PBMAs varies depending on the source and processing, commonly containing carbohydrates, fats, and proteins. However, their macronutrient levels often differ from cow's milk. For example, only soy-based PBMAs approach similar protein content (2.6–3.7%), while most other types tend to be lower in protein and fat (Jeske *et al.,* 2017; Mäkinen *et al.,* 2016; Qin *et al.,* 2022; Romulo, 2022). Carbohydrate and sugar contents are highly variable, naturally higher in rice or oat-based drinks, and significantly increased in flavored formulations (Vanga and Raghavan, 2018). In general, PBMAs contain fewer vitamins and minerals, like calcium and vitamin D, than cow's milk, but they are rich in health-promoting bioactive compounds such as antioxidants, which have drawn increasing

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interest from health-conscious consumers (Kasapidou *et al.,* 2023).

Plant-based milk has been gaining increasing popularity among consumers who are turning to healthier lifestyle choices such as plant-based diet, vegetarianism, and veganism (Andreani *et al.,* 2023; Aschemann-Witzel *et al.,* 2020; He *et al.,* 2020; Rosenfeld, 2018). Additionally, environmental concerns have also boosted its consumption since animal-based production is deemed unsustainable due to high water usage and gas emissions (Penha *et al.,* 2021; van Vliet *et al.,* 2020). Compared to cow's milk, plant-based milk production has a lower carbon footprint, thus supporting environmental and food security goals (Tachie *et al.,* 2023). Health issues such as lactose intolerance and a higher risk of cancer, hypertension, stroke, cardiovascular diseases, and hypercholesterolemia are also driving the shift toward plant-based milk (Kim *et al.,* 2019; Sethi *et al.,* 2016; Syed and Wu, 2018; Wu *et al.,* 2024; Yogeswara *et al.,* 2023).

The global market for plant-based beverages has grown significantly in recent years, reflecting the growing demand for these products. The demand for plant-based milk grew by 19% between 2019 and 2022 (GFI, 2022). Currently, soybean-based beverages dominate the market, but in the years to come, production of drinks made from other plant sources, like rice, oats, coconut, and almonds, is projected to increase (Banach *et al.,* 2022).

One of the most extensively grown and consumed legumes worldwide is the soybean (*Glycine max*)*,* which has a high protein content and other nutritional benefits (Langyan *et al.,* 2022). Unlike most legumes, soybeans offer high-quality protein with a protein digestibility corrected amino acid score (PDCAAS) and digestibility rates ranging from 92–100% and 95–98%, respectively (McClements *et al.,* 2019; Qin *et al.,* 2022). Soybeans contain 37.69% protein, 28.20% lipid, 4.29% ash, 5.44% crude fiber, 16.31% carbohydrate, and 8.07% moisture (Etiosa *et al.,* 2018). They are rich in minerals such as phosphor, calcium, magnesium, potassium, sodium, iron, and zinc (Tamangwa *et al.,* 2023). Soybean has a healthy fat profile, with low levels of saturated fatty acids (SAFA) and high levels of unsaturated fatty acids, such as polyunsaturated fatty acids (PUFA) and monounsaturated fatty acids (MUFA), resulting in a PUFA to MUFA to SAFA ratio of 58:26:16 (Szostak *et al.,* 2020). Previous clinical trials have shown that increased soy protein consumption may lower the risk of chronic illnesses, including cancer and cardiovascular disease (CVD). Additionally, studies have suggested that soy protein, which is rich in isoflavones, can improve the health of menopausal women and help prevent osteoporosis (Qin *et al.,* 2022). These facts make soybeans and their products excellent sources of plant-based protein.

Pigeon pea (*Cajanus cajan* (L.) Mill *sp.*) holds potential as an alternative to soybeans due to its comparable nutritional content. Despite its adaptability and presence in several Indonesian regions (e.g., Bali, Yogyakarta, and West Nusa Tenggara), its use remains limited among the local community to traditional dishes, and it is still underutilized in terms of processed food innovation (A'yuni *et al.,* 2022; Aries *et al.,* 2025; Azra *et al.,* 2025). This underutilization is largely due to limited public awareness, availability, and product development, as well as the currently unstable supply of pea. In contrast, pigeon pea is a dietary staple in many African countries (Ahmed and Hasan, 2014). Promoting pigeon pea-based food products in Indonesia could support local food diversification and strengthen food security.

Consumed fresh (immature) or dried (mature), pigeon pea is a tropical perennial pulse crop that contains significant amounts of proteins, carbohydrates, vitamins, minerals, and essential amino acids (Abebe, 2022). The seeds contain approximately 11.08–11.92% moisture, 62.78–69.82% carbohydrates, 21.70–24.20% protein, 1.49–1.61% fat, and 3.58–5.50% crude fiber on a dry weight basis (A'yuni *et al.,* 2022; Abebe, 2022). Pigeon pea has a better amino acid balance and lower fat content than soybeans. It also boasts higher levels of vitamins C, A, and E than common beans, with 25.13–28.21 mg/100 g, 1 248.83–2 303.86 µg/100 g, and 67.44–100.51 mg/100 g, respectively (A'yuni *et al.,* 2022). Furthermore, previous studies have reported that pigeon pea contain bioactive compounds including polyphenols and phytosterols, high micronutrients, and low saturated fat content, which may contribute to anti-inflammatory, antibacterial, antimicrobial, antioxidant, anti-carcinogenic, antidiabetic, hepatoprotective, and hypocholesterolemic effects (Wu *et al.,* 2024; Yang *et al.,* 2020; Yogeswara *et al.,* 2023).

Production of PBMA from pigeon pea alone is technologically feasible, however, the calculation of nutrient content showed protein content lower than the standard set for a plant-based milk. Combining pigeon pea and soybean in the development of plant-based milk alternatives is rare. It presents a strategic approach to enhance the nutritional profile, , and improve diversify sources functional properties. While soy provides a higher protein content and is well-established in PBMA production (McClements *et al.,* 2019; Qin *et al.,* 2022), pigeon pea offer complementary benefits, including its functional properties in the form of high levels of antioxidants, micronutrients, and dietary fiber content (A'yuni *et al.,* 2022; Abebe, 2022; Yang *et al.,* 2020). This combination can create a more balanced beverage with enhanced health benefits, especially for populations with limited access to animal proteins. Furthermore, using locally available crops like pigeon pea supports food sovereignty and sustainability efforts in Indonesia. By integrating both legumes, this formulation not only addresses nutritional adequacy but also encourages agricultural diversity and innovation in functional food development. This study aimed to evaluate the physicochemical properties, sensory acceptability, and potential health benefits of PBMA derived from pigeon pea and soybean.

MATERIALS AND METHOD

Materials

The materials used to produce the PBMA samples, such as pigeon pea was purchased from a local market in Denpasar, Bali, Indonesia, while sugar were obtained from a local market in Bogor, West Java, Indonesia. The pigeon pea was purchased in 250-g packages, with no specific brands or varieties. Meanwhile, the soybean was purchased from Rumah Tempe Indonesia in Bogor. Upon arrival in the laboratory, the ingredients were immediately stored in dry, airtight containers until further use.

Plant-based milk preparation

Pigeon pea and soybean were manually sorted, weighed, and washed with hot water, then soaked separately in water at a 1:3 (w/v) ratio for 12 h at 75 °C. After soaking, pigeon pea was boiled directly for 30 min, while soybeans were peeled before being boiled separately for 30 min. A 30-min boiling time was chosen for both legumes to reduce antinutritional factors, im-prove texture, and enhance flavor, based on preli-minary trials. After the boiling process, both pigeon pea and soybean were drained. To prepare the plant-based milk alternative (PBMA), the pigeon pea–soybean mixture was combined with water at a 1:5 (w/v) ratio and blended with kitchen blender until smooth. The mixture was then filtered with a muslin cloth, and 4% sugar was added to the filtrate to enhance the flavor and improve the sensory acceptability of the PBMA, reducing the bitter taste of soybeans (N'Kouka *et al.,* 2004). Finally, the filtrate was pasteurized at 80 °C for 30 min manually with kitchen stove and cooking pot, while continuously stirred. This study includes three PBMA formulas with pigeon pea and soybean pro-portions of 40:60, 50:50, and 60:40, respectively.

Proximate composition

The moisture content of the samples was determined by placing 3–5 g of it into a hot air oven and heated at 105 °C until its weight remained constant, based on the AOAC Official Method No. 930.15; meanwhile, the ash content was measured at 550 °C in a muffle furnace, following the AOAC Official Method No. 930.05 (AOAC, 2005). The protein level was determined by the Kjeldahl method AOAC Official Method No. 978.04 using a semi-automatic Kjeldahl analysis system, which includes a digestor (DT 208 Digestor™, FOSS Analytical, Denmark) and a distillator (KT 200 Kjeltec™, FOSS Analytical, Denmark) followed by manual titration to determine the amount of nitrogen present in the sample (AOAC, 2005). The crude protein content was then calculated using the nitrogen-to-protein conversion factor of 6.25. Meanwhile, a semi-automatic Soxhlet extraction instrument (ST 243 Soxtec™, FOSS Analytical, Denmark) was used to measure the fat content using the Soxhlet extraction method AOAC Official Method No. 930.09 (AOAC, 2005). The carbohydrate content was determined by difference using Formula 1.

Carbohydrate (%) =

100 - [Protein (%)+Fat (%)+Ash (%)+Moisture (%)] (1)

Color

A portable chromameter (CR-400; Konica Minolta Sensing, Inc., Osaka, Japan) was used to measure color parameters using CIE LAB color space (L*, a*, b*, C*, and h˚). Before measurement, a white tile was used to calibrate the device. The CIE LAB color space has three coordinate systems: lightness (L*) ranges from black (0) to white (100), while the a* coordinate indicates redness (+) and greenness (-), and the b* coordinate indicates yellowness (+) and blueness (-). Chroma (C*) and hue angle (h˚) are derived parameters calculated from the a* and b* coordinates.

Viscosity

A dial-reading viscometer (RVT DY300, Brookfield, USA) was used to measure the viscosity. Samples were put into a number-one spindle set and viscosity readings were taken at 100 rpm. Using a reference table known as "Brookfield Viscometer Factor Finder," torque readings were converted by Formula 2, and all measurements were recorded in centipoises (cP) (Brookfield Engineering Laboratories Inc., 2017 in Azra *et al.,* 2021).

Viscosity in cP (mPa·s) = Dial reading×factor .... (2)

Total soluble solids

Total soluble solids were determined with a hand-held refractometer (Master, ATAGO, Japan). The instrument was equipped with automatic temperature correction at 20 °C. The results were reported in °Brix.

pH

The pH values of the samples were determined using a benchtop pH meter (Starter 3100, OHAUS, USA). The instrument was calibrated prior to use. The final pH values were recorded according to the manufacturer's instructions.

Acceptance sensory evaluation

Thirty-five untrained panelists, selected from students and staff of the Department of Community Nutrition, IPB University, Indonesia, evaluated the plant-based milk alternatives (PBMA) made from pigeon pea and soybean based on appearance, aroma, texture, taste, aftertaste, and overall acceptability. A 9-cm hedonic line scale was used, where 0 cm indicated "extremely dislike" and 9 cm indicated "extremely like", with length of line reflecting the degree of liking for each sensory attribute. Panelists were instructed to rinse their palates with distilled water before and after evaluating each sample. All panelists were informed about the test procedure and uppon agreeing to be panelists, they signed the informed consent before the sensory evaluation started.

Descriptive sensory evaluation

Descriptive sensory evaluation was conducted only for the formula selected based on the results of the physicochemical analysis and sensory acceptance test. All training and assessment sessions were held at the sensory laboratory of the IPB University's Department of Community Nutrition. A total of 12 trained panelists, aged 20–25 years old, participated in the test. The panelists were chosen following ISO 8586:2023 guidelines and provided their consent before their involvement (ISO, 2023). They were selected because they were accustomed to drinking nut milk and had prior experience taking part in sensory tests. The panelists were also pre-screened to assess their sensitivity to certain stimuli. Following that, qualified panelists received additional training to ensure the precision of their assessments of sensory attributes. The panel met twice weekly for a maximum of 120 min over three weeks. The panel leader moderated the sessions to organize and direct the discussions.

The first stage of the test involved identifying the flavor and aroma descriptors of the PBMA sample. Panelists also identified possible reference standards and the intensity of these standards, which would be used to rate the attributes. The final list of descriptors, references, and the intensity of references was determined through consensus (Table 1). The discussion room was used for vocabulary development and training sessions, and separate sensory booths with artificial lighting were used for the sensory assessments.

Ten milliliters of samples and references were provided in plastic cups, covered with aluminum foil, and tested at room temperature. Each panelist evaluated the sample set twice to collect data, and the samples were presented using three-digit numbers in a randomized and blinded manner. Ratings of the intensity of the aroma and taste attributes were conducted using 15-cm scales, with "0" representing "none" and "15" representing "extremely strong." After assessing each sample, the panelists were asked to neutralize their senses of taste and smell using bread, water, and coffee powder.

Antioxidant activity and isoflavone content

Free radical scavenging activity was measured with the DPPH (2,2-diphenyl-1-picrylhydrazyl) method as described by Molyneux (2004) and Rahmawati *et al.* (2016). The measurement was performed with a UV-Vis Spectrophotometer (UV1800, Jenway 7325 Spectrophotometry, United Kingdom).

Table 1. The list of sensory attributes and descriptors used in descriptive sensory analysis of pigeon pea and soybean PBMA

Sensory Attributes and Descriptors	Standard Sample (Intensity Score)	References
Aroma		
Beany	10 g of soybean steamed for 30 min (13)	-
Sweet	10 mL of 15% sucrose solution (4)	McCarron *et al.* (2024)
Creamy	10 g of fresh coconut milk with a water-to-flesh ratio of 1.5:1 (11)	Nasution *et al.* (2018); Setiawan *et al.* (2022)
Cooked	10 g of cooked rice (12)	-
Cereal	10 g of oats (8)	Pointke *et al.* (2022)
Taste		
Sweet	10 mL of 10% sucrose solution (9)	McCarron *et al.* (2024); Pointke *et al.* (2022)
Beany	10 g of soybean steamed for 30 min (12)	-
Pigeon pea-like	10 g of pigeon pea steamed for 30 min (14)	-
Creamy	10 mL of coconut milk boiled for 3 min with a water-to-flesh ratio of 1.5:1 (11)	Setiawan *et al.* (2022)
Bitter	10 mL of 0.5% green tea solution (6)	Setiawan *et al.* (2022)
Salty	10 mL of 0.5% NaCl solution (4)	Pointke *et al.* (2022)

The concentrations of the samples ranged from 12.5, 25, 50, 100, and 200 mg/L (or ppm). Two milliliters of a 60 mg/L DPPH solution were combined with one milliliter of the sample, and the mixture was incubated at room temperature in the dark for half an hour, then absorbance was measured at 523 nm. The results are expressed as inhibition percentage (% inhibition).

Furthermore, the isoflavones such as daidzein, glycinin, and genistein were analyzed using high-performance liquid chromatography (HPLC) according to the AOAC Official Method 2008.03 – Total Soy Isoflavones in Dietary Supplements, Supplement Ingredients, and Soy Foods (Collison, 2008). The analysis was performed with an HPLC system (Thermo Scientific UltiMate™ 3000, Thermo Fisher Scientific, United States) equipped with a C18 column (250×4.6 mm) and an isocratic detector. Pure isoflavones (Sigma-Aldrich, USA) were used as the standard solution, and methanol was utilized as the mobile phase.

Statistical analysis

All data, including those from the sensory evaluation, are presented as means with their standard deviations. Experimental data (excluding sensory evaluation) were obtained from triplicate measurements. The significance of the analysis of variance (ANOVA) results was defined at $p<0.05$ with a 95% confidence interval. The post-hoc Duncan's multiple range test determined significant differences among the mean values. The software SPSS (version 16.0 for Windows) was used for all statistical analyses.

RESULTS AND DISCUSSION

Proximate composition

Pigeon pea and soybean are the primary ingredients of PBMA, and their chemical makeup must be taken into account to support the interpretation of its proximate and functional characteristics. A helpful reference point is provided by data from earlier studies, even though the current study did not measure the proximate composition of the raw ingredients used. Pigeon pea and soybean's typical proximate compositions as reported in published literature are shown in Table 2. Pigeon pea typically contain less fat than soybean but more moisture and carbohydrates. Table 3 shows variations in moisture, protein, fat, and carbohydrate content across PBMA formulations, which were probably caused by these compositional differences.

The moisture content for pigeon pea and soybean PBMA at different formulas ranged from 91.84–92.39% and they were significantly different ($p<0.05$) (Table 3). Meanwhile, it was reported that the moisture content of the almond and soymilk PBMA was 72.04–91.89% (Kundu *et al.,* 2018). When the amount of pigeon pea in the samples increased, so did the moisture content of PBMA. This was due to the higher moisture content of pigeon pea (11.08–11.92%) (A'yuni *et al.,* 2022) as compared to soybean (1.09–8.07%) (Etiosa *et al.,* 2018; Tamangwa *et al.,* 2023).

Table 2. Proximate composition of pigeon pea and soybean from the literature

Component (%)	Pigeon Pea	Soybean	References
Moisture	11.08–11.92	1.09–8.07	A'yuni *et al.* (2022); Etiosa *et al.* (2018); Tamangwa *et al.* (2023)
Ash	3.99–4.92	4.20–5.20	A'yuni *et al.* (2022); Etiosa *et al.* (2018); Tamangwa *et al.* (2023); Torres *et al.* (2007)
Protein	21.70–29.30	25.50–41.40	A'yuni *et al.* (2022); Abebe (2022); Etiosa *et al.* (2018); Sharma *et al.* (2014); Tamangwa *et al.* (2023); Torres *et al.* (2007)
Fat	1.49–2.36	16.30–32.38	A'yuni *et al.* (2022); Abebe (2022); Etiosa *et al.* (2018); Sharma *et al.* (2014); Tamangwa *et al.* (2023); Torres *et al.* (2007)
Carbohydrate	62.78–69.82	20.71–37.51	A'yuni *et al.* (2022); Abebe (2022); Etiosa *et al.* (2018); Tamangwa *et al.* (2023)

Table 3. Proximate composition of pigeon pea and soybean PBMA

Proximate Composition (%)	Formula (Pigeon Pea:Soybean)		
	F1 (40:60)	F2 (50:50)	F3 (60:40)
Moisture	91.84±0.12^{a}	92.26±0.05^{b}	92.39±0.06^{b}
Ash	0.12±0.01^{b}	0.11±0.01^{b}	0.09±0.01^{a}
Protein	1.48±0.03^{c}	0.98±0.01^{b}	0.80±0.02^{a}
Fat	1.04±0.04^{b}	0.86±0.02^{a}	0.81±0.02^{a}
Carbohydrate	5.52±0.11^{a}	5.78±0.09^{b}	5.91±0.02^{b}

Note: $^{a-c}$Different superscript letters in a row indicate a significant difference (*p*-value<0.05)

The initial moisture content of pigeon pea seeds may increase water retention during processing, which increases the final PBMA moisture content. Additionally, structural and compositional differences between pigeon pea and soybean, including differences in protein, fiber, and starch content, can affect water absorption and retention during soaking, grinding, and heating stages (Daryani *et al.,* 2024; Jamalullail *et al.,* 2023; Kakade *et al.,* 2019). Despite their apparent insignificance, the observed variations in moisture content are statistically significant and may have implications for product texture, stability, and consumer acceptability (McClements *et al.,* 2019). This comparison with almond and soymilk PBMA formulations shows how plant sources affect moisture characteristics, which is important when designing plant-based milk alternatives with optimal sensory and functional properties.

Ash content of pigeon pea and soybean PBMA samples significantly varied across different blend ratios, ranging from 0.09% in the 60:40 formula to 0.12% in the 40:60 formula (Table 2). These values differed significantly (p<0.05). According to Kundu *et al.* (2018), their PBMA made from soy and almond milk had ash content ranging from 0.81–3.02%. The observed trend shows that the ash content decreased as the percentage of pigeon pea increased. This suggests that the ash content of soybean (4.20–5.20%) (Etiosa *et al.,* 2018; Tamangwa *et al.,* 2023) is greater than that of pigeon pea (3.99–4.92%) (A'yuni *et al.,* 2022; Torres *et al.,* 2007).

All of the samples showed significant differences (p<0.05) in protein content, ranging from 0.80–1.48% (Table 3). The 40:60 formula had a signifi-cantly higher protein content than the 50:50 and 60:40 formulas. The results suggest that increasing the proportion of pigeon pea led to higher protein levels. The highest percentage of protein content was found in the pigeon pea and soybean PBMA ratio of 40:60, which contains the largest proportion of soybeans. This is in line with the fact that soybeans have a higher known protein content (25.50–41.40%) (Etiosa *et al.,* 2018; Sharma *et al.,* 2014; Tamangwa *et al.,* 2023) than pigeon pea (21.70–29.30%) (A'yuni *et al.,* 2022; Abebe, 2022; Torres *et al.,* 2007). Thus, the samples' protein content decreased as the amount of pigeon pea used increased. Similarly, Kundu *et al.* (2018) discovered that substituting almond milk for soymilk in PBMA decreased protein levels because almond milk has a lower protein concentration. This is supported by Jeske *et al.* (2017), who also reported that soymilk contains more protein than other types of PBMA.

The fat content of pigeon pea and soybean PBMA samples differed significantly (Table 3). The pigeon pea and soybean PBMA ratio 40:60 had the highest percentage of fat content, implying that soybeans contain more fat than pigeon pea (Table 3). The current finding complies with studies that indicated pigeon pea have low fat (1.49–2.36 g/100 g) (A'yuni *et al.,* 2022; Abebe, 2022; Torres *et al.*, 2007) as compared to soybean (16,3-32,38 g/100 g) (Etiosa *et al.*, 2018; Sharma *et al.,* 2014; Tamangwa *et al.,* 2023). Furthermore, previous studies reported that 100% soymilk contains a fat content of about 2.35% (Kundu *et al.,* 2018) and 1.8–3.5 g/100 mL (Jaeger *et al.,* 2024). The fat content of the PBMA samples decreases as the percentage of pigeon pea increases. This trend can be attributed to the lower fat content of pigeon pea, which eventually reduces the fat content of PBMA produced. Similar to the findings of earlier studies on soy milk-based ice cream substitutes by Asres *et al.* (2022), the fat content in soybeans provides the milk's rich flavor, color, body, texture, mouthfeel, and appearance, which are important sensory qualities of the product that are influenced by fat.

The carbohydrate content for pigeon pea and soybean PBMA samples differed significantly (p<0.05) and ranged from 5.52–5.91% (Table 3). This difference was due to the higher carbohydrate content of pigeon pea (62.78–69.82%) (A'yuni *et al.*, 2022; Abebe, 2022), which is greater than that of soybean (20.71–37.51%) (Etiosa *et al.,* 2018; Tamangwa *et al.,* 2023). Consequently, formulations containing a larger percentage of pigeon pea pro-duced a higher content of total carbohydrates. The 60:40 formula had the highest carbohydrate, and the one with a 60:40 ratio had the lowest (Table 3).

Physical characteristics of plant-based milk

The color parameters for pigeon pea and soybean PBMA at different blend ratios were as follows: lightness (L*) ranged from 59.74 to 68.57, greenness to redness (a*) from -0.53 to 0.68, yellowness (b*) from 6.60 to 8.13, chroma (C*) from 6.60 to 8.14, and hue angle (h˚) from 84.86 to 93.76˚ (Table 4). All the samples showed significant differences (p<0.05). In the CIE Lab* color space, L* means the sample's lightness (0= black, 100= white), a* means the sample's position between green (negative values) and red (positive values), and b* means the sample's position between blue (negative values) and yellow (positive values). While hue angle (h˚) describes the actual shade that is perceived (e.g., yellow, green, red), chroma (C*) indicates the color's intensity or saturation. These parameters are impor-tant because they measure objectively how plant-based milk look, which is a crucial component of consumer acceptance and product differentiation (Tobolková and Durec, 2023).

The color parameters L*, a*, b*, C*, and h˚ decreased as the proportion of pigeon pea in PBMA increased, indicating a change in color intensity (Table 4). Pigeon pea seeds have antinutrient compounds and natural pigments that contribute to their darker appearance, with L* values typically ranging from 30.70 to 31.64 (A'yuni *et al.,* 2022). These compounds, particularly abundant in darker seed genotypes common in Asia, have been associated with lower levels of lightness, in contrast to African varieties with cream or white seeds that contain smaller antinutrients (Odeny, 2007). This explains the observed decrease in L* as the proportion of pigeon pea increases in the PBMA formulations.

The viscosity for pigeon pea and soybean with varying blend ratios differed significantly (p<0.05) and varied between 11.42 and 12.50 (Table 4). The viscosity decreased as the proportion of pigeon pea in the PBMA production increased. This indicates that a higher percentage of pigeon pea leads to lower viscosity in PBMA, likely due to the higher moisture content introduced by the pigeon pea, resulting in a more liquefied consistency. This decrease in viscosity could affect the mouthfeel or texture, which is an important factor in determining if consumers will accept the newly developed PBMA (Daryani *et al.,* 2024).

The soluble solids content for pigeon pea and soybean PBMA at different blend ratios showed significant variations (p<0.05), ranging from 6.00°Brix to 9.00°Brix (Table 4). The 60:40 formula had a significantly higher soluble solids content compared to the 50:50 and 40:60 formulas. These results indicate that the soluble solids content increased as the proportion of pigeon pea in the PBMA increased. This significantly increased can be attributed to the higher carbohydrate content of pigeon pea (62.78–69.82%) (A'yuni *et al.,* 2022; Abebe, 2022) compared to soybeans (20.71–37.51%) (Etiosa *et al*., 2018; Tamangwa *et al*., 2023). These carbohydrates likely contribute to the higher concentration of soluble solids in formulations with more pigeon pea. A similar finding was reported by Meghrabi and Yamani (2023), where higher carbohydrate content in legume-based mixtures is associated with increased soluble solids. Higher soluble solids result from higher carbohydrate content, especially water-soluble sugars like sucrose, glucose, and fructose, which directly contribute to the soluble fraction (°Brix). Higher soluble carbohydrates raise soluble solid readings, which are indicators of sweetness and maturity, as demonstrated by this strong positive correlation in fruit studies (e.g., apples, tomatoes) (Jan and Kawabata, 2011; Kangli *et al.,* 2019).

The pH values of the samples varied significantly (p<0.05), with a narrow range of 6.69 to 6.72 (Table 4). The pH values slightly decreased as the proportion of pigeon pea in the PBMA increased. This result is similar to the study of Kundu *et al*. (2018), which reported that soymilk has a higher pH (7.39) than almond milk (6.92). These differences can be attributed to the varying acid compositions present in pigeon pea and soybean, including not only organic acids (such as citric, malic, and oxalic acids) but also differences in amino acid and fatty acid profiles. Pigeon pea protein is rich in hydrophilic amino acids like glutamic and aspartic acid, which are also abundant in soybean but may be present in slightly different proportions (Haji *et al.,* 2024; Oshodi *et al.,* 1993). In terms of fatty acids, soybean contains a higher proportion of unsaturated fatty acids, particularly linoleic and oleic acids, while pigeon pea lipids are predominantly saturated fatty acids with a lower total fat content and a lower level of oleic acid *(Oshodi et al.,* 1993). These compositional differences may contribute to the slightly more acidic nature of pigeon pea-based formulations.

Sensory acceptance evaluation

The attributes assessed in the acceptance test for pigeon pea and soybean plant-based milk were appearance, texture, aroma, taste, aftertaste, and overall acceptability. The samples' mean evaluations are presented in Table 5. The sensory characteristics for all attributes did not significantly differ among the samples (p>0.05), indicating no significant changes in sensory attributes across different pigeon pea and soybean ratios in PBMA samples.

Table 4. Physical characteristics of pigeon pea and soybean PBMA

Parameters	Formula (Pigeon Pea: Soybean)		
	F1 (40:60)	F2 (50:50)	F3 (60:40)
Color			
L*	68.57±1.26^{c}	65.37±0.76^{b}	59.74±0.91^{a}
a*	-0.53±0.13^{a}	0.68±0.02^{c}	0.35±0.07^{b}
b*	8.13±0.50^{b}	7.59±0.04^{b}	6.60±0.32^{a}
C*	8.14±0.49^{b}	7.62±0.04^{b}	6.60±0.32^{a}
h°	93.76±1.12^{c}	84.86±0.10^{a}	87.01±0.43^{b}
Color intensity (CIE)			
Viscosity (cP)	12.50±0.25^{b}	11.67±0.14^{a}	11.42±0.14^{a}
Soluble solids (°Brix)	6.00±0.00^{c}	7.50±0.71^{b}	9.00±0.00^{a}
pH	6.72±0.00^{a}	6.70±0.00^{b}	6.69±0.01^{c}

Note: $^{a-c}$Different superscript letters in a row indicate a significant difference (p-value<0.05)

Table 5. Sensory acceptance evaluations of pigeon pea and soybean PBMA

Sensory Attributes	Formula (Pigeon Pea:Soybean)		
	F1 (40:60)	F2 (50:50)	F3 (40:60)
Appearance	5.37±1.91[a]	5.47±1.62[a]	5.24±1.84[a]
Aroma	5.45±1.91[a]	5.52±1.89[a]	5.40±1.99[a]
Texture	5.82±1.98[a]	5.75±1.60[a]	5.95±1.93[a]
Taste	5.83±1.95[a]	5.32±2.21[a]	5.77±2.11[a]
Aftertaste	5.97±1.54[a]	5.76±1.51[a]	5.94±1.51[a]
Overall acceptance	5.75±1.48[a]	5.81±1.56[a]	5.78±1.50[a]

Note: [a-c] A significant difference is indicated by different superscript letters in a row (*p*-value<0.05)

The appearance, aroma, texture, taste, aftertaste, and overall acceptance of the samples in this study were generally neutral, falling within the range of "neither like nor dislike" (4.50–5.95). These evaluations were slightly lower than those of PBMA made from soybean and almond, as reported by Kundu *et al.* (2018), which ranged from "like slightly" to "like very much" (6.47–8.5). This discrepancy may be due to the use of almonds in their study, as the increased use of almonds can enhance the color, taste, and mouthfeel of plant-based milk.

Consumers may reject legume-based milk substitutes such as soybean and pea (Romulo, 2022; Sethi *et al.*, 2016) due to their distinctive beany and earthy aroma, attributed to the presence of hexanol from plant lipid oxidation and their unfamiliar taste (Meghrabi and Yamani, 2023). The industry also has to deal with two major issues: a chalky mouthfeel caused by insoluble large particles and a beany off-flavor caused by lipoxygenase activity on unsaturated fatty acids (Aydar *et al.,* 2020; Durand *et al.,* 2003; Sethi *et al.,* 2016). This is evidenced by the lower acceptability of soy and peanut milk alternatives, which receive "slightly/moderately liked" evaluations (Meghrabi and Yamani, 2023). Therefore, improving the sensory properties while maintaining the health benefits is essential to meet consumer preferences.

Descriptive sensory evaluation

In this study, the descriptive sensory evaluation was carried out with a consensus method for a selected sample. A trained panel of twelve participants aged 20–25 years old were selected for their sensitivity and sensory analysis skills to perform the descriptive sensory evaluation. To maximize the functional potential of pigeon pea, including its bioactive compounds such as phytosterols, polyphenols, and vitamins C, A, and E, the 50:50 formula was selected, as its acceptance test result was not significantly different from the 60:40 formula with a higher proportion of soybean. The spider plot of the aroma and taste characteristics of the pigeon pea and soybean PBMA is shown in Figure 1.

The panelists identified these aroma descriptors, beany, cooked, creamy, cereal, and sweet, in the PBMA sample. These sensory attributes were derived from previous studies that demonstrated the cereal (Pointke *et al.,* 2022) and sweet (McCarron *et al.,* 2024) aromas of soymilk and other PBMAs. According to the panelists, the most commonly described aroma attributes in the pigeon pea and soybean PBMA sample were beany and cooked aroma, with sweet being the weakest note (Figure 1). The prevalence of beany and cooked scents is probably caused by certain volatile compounds that are present in legumes naturally and are created during processing.

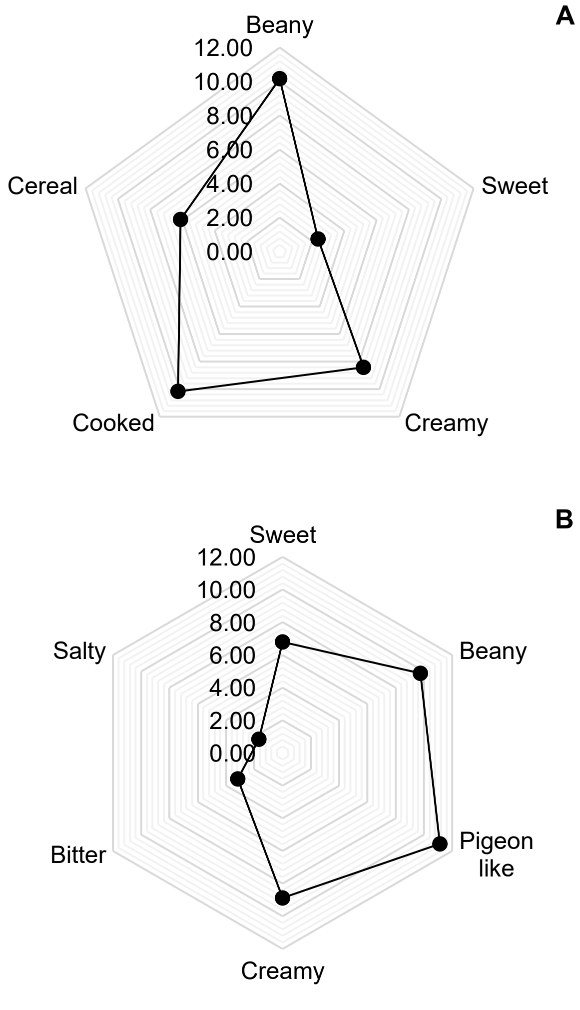

Figure 1. Sensory descriptive profile of pigeon pea and soybean PMBA with a ratio of 50:50 on aroma (A) and taste (B)

Various key compounds may contribute to the aroma of soymilk (Pointke *et al.,* 2022). One of the main causes of the beany aroma is 1-hexanol, a volatile substance that is created when plant lipids oxidize (McCarron *et al.*, 2024; Pointke *et al.*, 2022). This characteristic is often associated with negative consumer perception of legume-based milk substitutes. Meanwhile, the cooked aroma was caused by 1-octen-3-ol and pentanal, which are widely present in soy-based drinks (Pointke *et al.*, 2022). The pigeon pea and soybean PBMA have a creamy aroma because of the high fatty acid levels, such as dodecanoic acid, oleic acid, and hexadecenoic acid (Pointke *et al.,* 2022). Those compounds most likely contributed to the milky or creamy aroma attributes. The cereal aroma was presumably due to the aldehydes compounds such as 2-methylpropanal (McCarron *et al.,* 2024) that may exist in pigeon pea and soybean PBMA. Lastly, the sweet aromas are less pronounced, likely due to a lower presence of sugar-derived volatiles such as 4-methyl benzaldehyde that come from the reaction between reducing sugars with amino acids and tetradecane (McCarron *et al.,* 2024; Pointke *et al.,* 2022).

The panelists identified the following taste descriptors: creamy, sweet, bitter, salty, beany, and pigeon pea-like in the samples (Figure 1). The weakest tastes detected were bitter and salty, with a pigeon pea-like flavor dominating the palate. The flavors determined by the panelists were consistent with findings from previous studies on oat-based milk alternatives, namely bitter, salty, and sweet (McCarron *et al.,* 2024). The bitter taste in pigeon pea and soybean PBMA is considered to have negative properties (N'Kouka *et al.,* 2004). Meanwhile, the 4% sugar used as a sweetener in this study successfully masked the bitterness. This added sugar was less than the previous study to result in desirable flavor changes, reducing the bitter taste descriptor in soy milk with 11.0% and 9.4% sugar (N'Kouka *et al.*, 2004).

Antioxidant activity and isoflavone content

The PBMA product made from pigeon pea and soybean with a ratio of 50:50 has been analyzed for its isoflavone content (daidzein, genistein, and glycitein) and antioxidant activity (Table 6). The analysis showed that PBMA contained 0.56% daidzein, 0.37% genistein, and 0.09% glycitein. These levels are less than those found in fermented soybean milk, which has 9.01% genistein and 12.09% daidzein (Lodha *et al.,* 2021). PBMA's lower isoflavone levels could be the result of variations in fermentation and processing. During fermentation, isoflavone glycosides like genistin and daidzin are hydrolyzed by β-glucosidase activity to their more bioavailable and potent antioxidant aglycone forms, genistein and daidzein (Callou *et al.,* 2010).

Table 6. Isoflavone content and antioxidant capacity of pigeon pea and soybean PBMA (50:50)

Parameters	Value
Daidzein (g/100 g)	0.56
Glycitein (g/100 g)	0.09
Genistein (g/100 g)	0.37
Antioxidant capacity (%)	91.904

Pigeon pea is naturally high in flavonoids that have anti-inflammatory and antioxidant qualities. These include cajanin and cajanol, as well as aglycone isoflavones like genistein (0.32–0.78 mg/100 g DM) and daidzein (5.12–9.03 mg/100 g DM) (Tungmunnithum *et al.,* 2021). The contribution of pigeon pea, where daidzein is not only predominant but also recognized for having a higher bioavailability and more potent antioxidant activity than its glycosylated forms, is probably responsible for the PBMA formulation's comparatively high daidzein content. In contrast, the isoflavone content of typical soybean profiles is dominated by glycosylated and malonylated forms, specifically daidzin, genistin, malonylgenistin, glycitin, and malonyldaidzin, rather than aglycones (Callou *et al.,* 2010). These variations in composition show how PBMA's nutritional profile is influenced by the sources of its ingredients as well as its processing techniques.

The isoflavone content in PBMA of pigeon pea and soybean in a ratio of 50:50 reflects the product's functional potential in supporting health. According to Maleki *et al.* (2015), nut and seed milk are rich in antioxidants, which reduce the risk of cardiovascular diseases, cancer, atherosclerosis, and diabetes by preventing free radicals from oxidizing nucleic acids, proteins, lipids, and DNA. Daidzein is a powerful antioxidant with anti-aging, anti-inflammatory, and anti-cancer effects, and it protects against cardiovascular disease, diabetes, and osteoporosis. Meanwhile, genistein has been reported to be able to affect Alzheimer's disease in mice (Pistollato *et al.,* 2018).

Apart from the isoflavone content, the antioxidant activity of the 50:50 pigeon pea and soybean PBMA sample reached 91.90%, showing a very high ability to ward off free radicals. This antioxidant activity is much higher than other PBMAs, namely hazelnut milk substitute (50.47%) (Maleki *et al.,* 2015), sesame milk substitute (19.3%) (Fitrotin *et al.,* 2015), rice milk substitute (34.95%) (Ismail *et al.,* 2018) and soy product extracts (41.6%-81.6%) (Baghbadorani *et al.,* 2017). The content of bioactive compounds in pigeon pea and soybean, such as isoflavones and phenolics, influences this antioxidant activity. The results of this study are also in line with Tungmunnithum *et al*. (2021) who stated that antioxidant activity is related to the total phenolic component. This product's high antioxidant activity indicates its great potential in preventing oxidative stress, which is known to contribute to the development of degenerative diseases such as diabetes, heart disease, and cancer.

This research indicates that PBMA, made from pigeon pea and soybean, can be an alternative functional drink with health benefits. Its high content of isoflavones and antioxidant activity provides an opportunity to support a healthy lifestyle while preventing degenerative diseases. Thus, this product has the prospect of being a functional food innovation based on local ingredients, supporting food diversification and improving public health.

CONCLUSION

The plant-based milk alternatives (PBMA) made with varying ratios of pigeon pea and soybean showed significant differences in their physicochemical characteristics but no notable differences in sensory acceptability. While moisture, carbohydrate, and soluble solids content increased, ash, protein, fat, color, viscosity, and pH levels decreased as the proportion of pigeon peas in the PBMA increased. Although they have a beany aroma that some consumers may not prefer, the sweet and creamy notes with reduced bitterness contribute to a desirable flavor, making them suitable as PBMA. Furthermore, daidzein was identified as the predominant isoflavone in the PBMA formulation, which contained a 50:50 ratio of pigeon pea and soybean. The product's suitability as a functional PBMA option is highlighted by these qualities and the antioxidant potential derived from pigeon peas.

ACKNOWLEDGMENT

This research was funded by *Dana Abadi Perguruan Tinggi-Lembaga Pengelola Dana Pendidikan* (DAPT-LPDP) through the national research collaboration funding program (*Riset Kolaborasi Nasional*) with the Grant No. 561/IT3.D10/PT.01.03/P/B/2023.

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