

The initial characterization of the physicochemical properties of roasted bee pollen powder *Heterotrigona itama* from East Kalimantan as a coffee alternative

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Abstract. Bee pollen from *Heterotrigona itama* is recognized as a natural source of bioactive compounds, including phenolics, flavonoids, vitamins, and essential nutrients, making it a promising candidate for development as a functional beverage with lower caffeine content compared to conventional coffee. Processing, particularly roasting, is a key factor that influences the physicochemical attributes, nutritional quality, and bioactive activities of the final product. This study investigated the effects of different roasting temperatures (120–160 °C) and times (10–30 minutes) on the physicochemical properties, bioactive compounds, and antioxidant capacity of bee pollen. Parameters evaluated included pH, solubility, vitamin C, total sugar, color attributes (L*, a*, b*, hue°), and proximate composition. Results revealed that higher roasting intensity decreased pH (5.83 to 5.21) and vitamin C content, whereas solubility improved, with the highest value at 120 °C for 20 minutes (80.6 ± 0.91%). Proximate analysis of roasted samples showed 6.21% moisture, 18.35% protein, 5.76% fat, 3.91% ash, and 62.08% carbohydrate. Roasting also darkened color due to Maillard reactions. Overall, medium roasting preserved nutrients while enhancing bioactive properties, highlighting roasted bee pollen as a potential functional coffee substitute with added health benefits.

1. Introduction

Coffee is one of the most popular beverages worldwide, including in Indonesia. It not only serves as a refresher and energy booster, but has also become an integral part of the modern lifestyle. Data from the International Coffee Organization (ICO) shows that global coffee consumption continues to increase year after year, driven by growing public awareness of coffee's health benefits, social value, and sensory enjoyment [1]. Indonesia, as one of the world's largest coffee producers, plays a vital role in the global coffee supply. Coffee also holds a strategic position in the national economy and is a highly valuable plantation commodity. However, coffee consumption is not without its share of health concerns, particularly those related to its caffeine content [2]. However, excessive caffeine consumption can cause side effects, such as sleep disturbances (insomnia), anxiety, increased heart rate, and even dependence [3-4]. Some individuals also have a high sensitivity to caffeine, preventing them from consuming large amounts of coffee [5]. This condition has

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prompted research to find alternative beverages that resemble coffee, both in terms of sensory and functional properties, but with lower or even no caffeine. One potential natural ingredient that could be developed as a coffee alternative is bee pollen.

Bee pollen is a natural product collected by worker bees from flowers and mixed with nectar and digestive enzymes [6]. It is known as a "superfood" because it contains a variety of health-beneficial bioactive substances, such as protein, essential amino acids, fatty acids, vitamins, minerals, flavonoids, and phenolic compounds [7-9]. Its high nutritional content makes bee pollen often used as a natural supplement to increase stamina, support the immune system, and prevent various degenerative diseases [7] [10]. One bee species that produces bee pollen *H. itama*, a stingless bee that has recently been increasingly cultivated in East Kalimantan. *H. itama* is known to produce bee pollen with unique chemical and bioactive characteristics, influenced by the biodiversity-rich local flora of East Kalimantan [11-13]. The potential for bee pollen utilization from *H. itama* is enormous, but so far, its use is still limited to supplementation in capsule or natural powder form without further processing. One effort to increase the diversification of bee pollen-based products is to process it into a roasted powder drink resembling coffee. The roasting process of food ingredients is known to modify physicochemical characteristics, such as color, aroma, taste, and bioactive compound profiles [14]. In coffee, roasting is a crucial step that determines key sensory characteristics [15-16]. The same can be applied to bee pollen, producing a powder product with a distinctive aroma, brownish color, and unique flavor that resembles coffee, despite being caffeine-free or with very low caffeine content. Thus, roasted bee pollen powder has the potential to be a functional coffee alternative for consumers who want a coffee-like sensation without the health risks of excess caffeine.

Characterizing the physicochemical properties of roasted bee pollen is a crucial initial step before further developing this product as a coffee alternative. Physicochemical properties encompass various parameters such as moisture content, ash content, protein content, fat content, carbohydrate content, pH, color, and solubility [17]. Through this initial characterization, an overview of the quality, stability, and potential health benefits of roasted bee pollen powder can be obtained. Research on the use of bee pollen as an alternative beverage ingredient is still relatively limited, especially in Indonesia. Previous studies have focused more on the biological activities of bee pollen, such as antioxidant, antimicrobial, and immunomodulatory activity [12] [18-19], while exploration in processed food products such as beverages is still rare. Therefore, this research represents an important breakthrough that opens up new opportunities in utilizing bee pollen as an ingredient in functional food innovations. From a socio-economic perspective, developing alternative coffee drinks from bee pollen can also provide added value for local beekeepers in East Kalimantan. Currently, the primary product of *H. itama* bee cultivation is honey, while bee pollen tends to be underutilized [20]. The innovation of bee pollen-based beverage products is expected to increase beekeeping product diversification, open new business opportunities, and increase the income of beekeepers. This aligns with government efforts to encourage local-based economic development and the sustainable use of biological resources. This research is expected to produce an alternative coffee beverage product that not only has a unique, coffee-like flavor but also offers health benefits due to its bioactive compounds. Furthermore, this product development can enrich Indonesia's diverse range of functional foods, particularly those from East Kalimantan, which boasts extraordinary biodiversity. This can also support efforts to promote local products to national and international markets.

2. Materials and Methods

2.1 Materials

Bee pollen of *H. itama* was collected from stingless bee in local farms L3 bangun Rejo, East Kalimantan, Indonesia. The raw pollen was manually cleaned and oven-dried at 40–45 °C until the moisture content was below 10%. All chemicals such as ethanol, AlCl₃, and Na₂CO₃ were of analytical grade (pro-analysis) and obtained from reputable suppliers (Merck and Sigma-Aldrich),

2.2 Sample Preparation

The dried bee pollen was roasted using an electric roaster (merk Sonifer SF-3561, China) at different temperatures (120 °C, 140 °C, and 160 °C) for 10, 20, and 30 min. After roasting, the samples were ground into a fine powder using a high-speed blender and subsequently sieved through a 60-mesh sieve to obtain a homogeneous roasted bee pollen powder.

2.3 Proximate analysis

2.3.1 Moisture content determination

Moisture content was determined according to the official method of AOAC [21] using the oven-drying procedure. Approximately 5 g of homogenized sample was accurately weighed into a pre-dried and pre-weighed aluminum dish. The dish containing the sample was placed in a hot air oven at 105 ± 2 °C for 3–5 h until a constant weight was obtained. After drying, the samples were cooled in a desiccator for 15–30 min and reweighed. The drying–cooling–weighing cycle was repeated until the difference between two consecutive weighings was less than 0.001 g. The moisture content was expressed as the percentage of weight loss relative to the initial weight of the sample, calculated using the following equation:

$$\text{Moisture content}(\%) = \frac{w_1 - w_2}{w_1 - w_0} \times 100 \quad (1)$$

where W₀ is the weight of the empty dish (g), W₁ is the weight of the dish with the sample before drying (g), and W₂ is the weight of the dish with the sample after drying (g).

2.3.2 Ash content determination

Ash content was determined according to AOAC [21] using the dry ashing method. About 5 g of sample was weighed into a pre-weighed porcelain crucible and incinerated in a muffle furnace at 550 ± 25 °C for 4–6 h until a constant weight was obtained. The crucibles were cooled in a desiccator and reweighed. Ash content (%) was calculated as the weight of residue relative to the initial sample weight.

$$\text{Ash content}(\%) = \frac{W_2 - W_0}{W_1 - W_0} \times 100 \quad (2)$$

where W₀ is the weight of the empty crucible (g), W₁ is the weight of the crucible with sample before ashing (g), and W₂ is the weight of the crucible with ash after ashing (g).

2.3.3 Protein content determination

Protein content was determined by the Kjeldahl method according to AOAC [21]. Approximately 1 g of homogenized sample was digested with concentrated sulfuric acid in the presence of a catalyst until a clear solution was obtained. The digested sample was then neutralized with sodium hydroxide, distilled, and the liberated ammonia was collected in a boric acid solution. The distillate was titrated with standardized hydrochloric acid (HCl). Total nitrogen content was calculated and multiplied by a conversion factor of 6.25 to estimate crude protein content. The protein content was calculated according to the following equation:

$$\text{Protein content}(\%) = \frac{(V \times N \times 14.0007 \times F)}{W} \times 6.25 \times 100 \quad (3)$$

where: V = volume of HCl used for titration (L), N = normality of HCl, 14.007 = atomic weight of nitrogen (g/mol), F = correction factor (if applicable), W = weight of the sample (mg), 6.25 = nitrogen-to-protein conversion factor

2.3.4. Fat content determination

Fat content was determined according to AOAC [21] using the Soxhlet extraction method. Approximately 2–5 g of homogenized and pre-dried sample was wrapped in filter paper and placed in a Soxhlet extractor. Petroleum ether (boiling point 40–60 °C) was used as the solvent. The extraction was carried out for 6–8 h until the solvent in the siphon tube became colorless, indicating complete extraction. After extraction, the solvent was evaporated, and the flask containing the extracted fat was dried in an oven at 105 ± 2 °C, cooled in a desiccator, and weighed to a constant weight. The fat content was calculated as:

$$\text{Fat content(\%)} = \frac{(W_2 - W_1)}{W_s} \times 100 \quad (4)$$

Where: W_1 = weight of empty flask (g), W_2 = weight of flask + extracted fat (g), W_s = weight of sample (g)

2.3.5 Carbohydrate content (By Difference)

Carbohydrate content was calculated by difference according to common proximate analysis practice. Carbohydrate (%) on a wet weight basis was calculated using the following equations depending on whether crude fiber was determined: Carbohydrate (%) = $100 - (\% \text{Moisture} + \% \text{Protein} + \% \text{Fat} + \% \text{Ash})$

2.4. Determination of Total Sugar Content

The total sugar content of roasted bee pollen powder was determined using the phenol-sulfuric acid method [22] with slight modification. A sample solution (1 mL) was mixed with 1 mL of 5% phenol and 5 mL of concentrated sulfuric acid. The mixture was incubated at room temperature for 30 minutes, and the absorbance was measured at 490 nm using a UV-Vis spectrophotometer. Glucose was used as the standard, and results were expressed as mg glucose equivalents per g dry weight (mg GE/g DW).

2.5. pH Measurement

The pH of the sample was measured using a digital pH meter [21]. Approximately 10 g of the homogenized sample was dispersed in 100 mL of distilled water (1:10 w/v). The mixture was stirred and allowed to equilibrate for 5 min. The pH was then determined by immersing the calibrated electrode into the sample solution at room temperature (25 ± 2 °C). Calibration of the instrument was carried out using standard buffer solutions at pH 4.0 and 7.0 before measurement.

2.6 Vitamin C analysis

Vitamin C content was determined using the 2,6-dichlorophenolindophenol (DCPIP) titration method according to [21] [23]. Approximately 5 g of sample was homogenized in 50 mL of 3% (w/v) metaphosphoric acid solution and filtered. An aliquot of 10 mL extract was titrated with standardized DCPIP solution until a light pink color persisted for 15 seconds. The vitamin C content was expressed as mg ascorbic acid per 100 g sample, calculated based on the DCPIP volume consumed.

2.7 Color Measurement

Color parameters (L^* , a^* , b^*) were determined using a colorimeter [21]. The instrument was calibrated with a standard white tile prior to measurement. Approximately 5 g of homogenized sample was placed in a transparent sample holder, and color values were recorded in triplicate at room temperature. The total color difference (ΔE^*) compared to the reference (control) sample was calculated as:

$$\Delta E^* = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \tag{5}$$

where L_0^* , a_0^* , and b_0^* are the color parameters of the reference sample, and L^* , a^* , b^* are the parameters of the tested sample.

2.8 Solubility Measurement

Solubility was determined according to [21] with slight modification. Approximately 1 g of sample was dispersed in 100 mL of distilled water in a centrifuge tube, vortexed for 5 min, and then heated in a water bath at 37 °C for 30 min. The suspension was centrifuged at 3000 rpm for 15 min, and the supernatant was collected. An aliquot of 25 mL of the supernatant was transferred into a pre-weighed dish and dried in an oven at 105 ± 2 °C until constant weight. Solubility (%) was calculated as:

$$\text{Solubility (\%)} = \frac{\text{Weight of dried supernatant solids}}{\text{weight of sample}} \times 100 \tag{6}$$

2.9 Experimental Design and Data Analysis

The experiment was designed as a completely randomized design (CRD) with nine roasting conditions, with each treatment conducted in triplicate ($n = 3$). Data were expressed as mean \pm standard deviation. Statistical analysis was performed using one-way ANOVA to evaluate the effect of roasting conditions, followed by Duncan’s multiple range test at a 95% confidence level.

3. Results and Discussion

3.1. Proximate Composition of Roasted Bee Pollen

Proximate analysis of roasted *Heterotrígona itama* bee pollen powder showed changes in chemical composition influenced by temperature and roasting time in table 1. Generally, increasing temperature and roasting time decreased moisture, protein, and fat content but increased carbohydrate content, while ash content remained relatively stable with a slight decrease.

Table 1. The effect of roasting temperature on the nutritional value of bee pollen *H. itama*

Roasting Condition	Proximate analysis (%)				Carbohydrate (%)
	Moisture content	Ash content	Protein content	Fat content	
80°C 10min	6.81 \pm 0.11 ^a	2.77 \pm 0.12 ^a	22.27 \pm 0.37 ^a	9.29 \pm 0.21 ^a	59.39 \pm 0.22 ^h
80°C 20min	6.28 \pm 0.09 ^b	2.63 \pm 0.33 ^{ab}	21.89 \pm 0.27 ^{ab}	8.91 \pm 0.14 ^b	60.15 \pm 0.42 ^g
80°C 30min	5.86 \pm 0.11 ^c	2.62 \pm 0.23 ^{ab}	21.63 \pm 0.55 ^b	8.86 \pm 0.11 ^b	60.59 \pm 0.38 ^g
120°C 10min	5.51 \pm 0.19 ^d	2.59 \pm 0.12 ^{ab}	21.35 \pm 0.51 ^{bc}	8.71 \pm 0.34 ^{bc}	61.68 \pm 0.34 ^f
120°C 20min	5.12 \pm 0.22 ^e	2.51 \pm 0.14 ^b	20.67 \pm 0.06 ^{cd}	8.45 \pm 0.25 ^{cd}	62.91 \pm 0.38 ^e
120°C 30min	4.76 \pm 0.22 ^f	2.45 \pm 0.77 ^b	20.76 \pm 0.25 ^c	8.39 \pm 0.22 ^{cd}	63.34 \pm 0.35 ^d
160°C 10min	4.35 \pm 0.01 ^g	2.46 \pm 0.33 ^b	20.43 \pm 0.24 ^{cd}	8.08 \pm 0.34 ^{cd}	64.79 \pm 0.89 ^c

160°C 20min	4.14 ± 0.25 ^{gh}	2.29 ± 0.32 ^{bc}	20.12 ± 0.48 ^d	7.64 ± 0.88 ^d	65.96 ± 0.43 ^b
160°C 30min	3.52 ± 0.17 ^h	2.09 ± 0.24 ^c	19.98 ± 0.23 ^d	7.51 ± 0.11 ^e	67.11 ± 0.32 ^a
Values are expressed as mean ± standard deviation (n=3). Different superscript letters within the same column indicate significant differences among roasting conditions at p < 0.05 (one-way ANOVA followed by Tukey's HSD test).					

The proximate composition of bee pollen was significantly affected by roasting temperature and duration ($p < 0.05$). Moisture content decreased steadily with increasing roasting severity, from 6.81% at 80°C for 10 min to 3.52% at 160°C for 30 min. This reduction is associated with the enhanced evaporation of free and bound water during thermal treatment. Lower moisture levels may improve storage stability by reducing water activity; however, excessive heating may negatively affect heat-sensitive bioactive compounds [24].

Ash content exhibited a gradual decline as roasting temperature and time increased. Bee pollen subjected to mild roasting at 80°C (10–30 min) retained higher ash values compared to samples roasted at 120–160°C, particularly at longer durations. This trend suggests that mineral components in bee pollen are sensitive to intensive thermal processing, which may alter their stability and retention [8]. Similar behavior has been reported in other thermally processed food matrices.

Protein content decreased significantly with increasing roasting temperature and duration. The highest protein value was observed at 80°C for 10 min, while prolonged roasting at higher temperatures resulted in a marked reduction. This decrease can be attributed to protein denaturation, aggregation, and participation in non-enzymatic browning reactions, particularly the Maillard reaction between amino acids and reducing sugars [25]. These reactions reduce the measurable crude protein fraction and are commonly intensified under high-temperature roasting conditions [26]. A decreasing trend was also observed in fat content as roasting intensity increased. Mild roasting resulted in only minor reductions, whereas roasting at 160°C led to substantial losses in fat content. This reduction is likely related to thermal oxidation, volatilization of unsaturated fatty acids, and degradation of lipid-associated bioactive compounds, which are accelerated at elevated temperatures [27-29].

In contrast, carbohydrate content increased significantly with increasing roasting temperature and duration, reaching its highest value at 160°C for 30 min. This increase is mainly attributed to the relative concentration effect, as reductions in moisture, protein, fat, and ash proportionally increased the calculated carbohydrate fraction [30]. In addition, thermal processing may induce carbohydrate-related reactions, including Maillard reactions and sugar transformations, which influence carbohydrate composition [31]. Overall, the results indicate that roasting conditions play a critical role in determining the proximate profile of bee pollen, with mild roasting conditions being more favorable for preserving its nutritional quality.

3.2. Total sugar, pH, vitamin C, and solubility

Roasting temperature and duration significantly affected total sugar, pH, vitamin C, and solubility of bee pollen ($p < 0.05$) shown in Table 2. Total sugar content decreased significantly with increasing roasting severity, as indicated by distinct superscript groupings (a–i). The highest value was observed at 80°C for 10 min, while the lowest occurred at 160°C for 30 min. This reduction is attributed to sugar degradation through caramelization and participation in Maillard reactions under elevated temperatures [31-32]. The pH values also showed a significant decreasing trend with increasing roasting temperature and time. Mild roasting treatments (80°C) retained significantly higher pH values than intensive roasting at 160°C. The decline in pH suggests the formation of acidic compounds and Maillard reaction intermediates during thermal processing [33]. Furthermore, protein degradation during heating also releases free amino acid groups, which contribute to increased acidity [26] [33].

Vitamin C content exhibited the most pronounced thermal sensitivity, with significant differences observed among nearly all roasting conditions. The highest retention was obtained under mild roasting, whereas severe roasting resulted in a reduction exceeding 60%. This confirms the heat-labile nature of ascorbic acid and its suitability as an indicator of thermal degradation [24]. In contrast, solubility showed a non-linear response to roasting. Solubility increased significantly up to 120°C for 20 min, followed by a decline at higher temperatures and longer durations. Moderate roasting significantly enhanced solubility compared to both mild and severe conditions, likely due to partial disruption of cellular matrices and macromolecular structures [34]. Excessive roasting may promote aggregation and formation of insoluble complexes, reducing solubility. Moderate roasting (120°C, 20 min) represents an optimal compromise between solubility enhancement and nutrient retention, whereas high-temperature, long-duration roasting leads to significant nutritional losses [35].

Table 2. Effect of Roasting Temperature on Total Sugar, pH, Vitamin C, and Solubility of *H. itama* Bee Pollen.

Roasting Condition	Total gula (g/100 g)	pH	Vitamin C (mg/100 g)	Solubility (%)
80°C 10min	21.41 ± 0.52 ^a	5.83 ± 0.11 ^a	42.23 ± 0.40 ^a	72.33 ± 1.01 ^g
80°C 20min	20.74 ± 0.47 ^b	5.74 ± 0.78 ^{ab}	38.53 ± 0.35 ^b	73.92 ± 1.02 ^f
80°C 30min	19.92 ± 0.44 ^c	5.65 ± 0.33 ^b	32.17 ± 0.28 ^c	75.64 ± 0.38 ^e
120°C 10min	18.31 ± 0.41 ^d	5.57 ± 0.22 ^c	24.35 ± 0.32 ^d	78.19 ± 0.19 ^c
120°C 20min	17.54 ± 0.38 ^e	5.42 ± 0.44 ^d	22.66 ± 0.30 ^e	80.62 ± 0.91 ^a
120°C 30min	16.4 ± 0.36 ^f	5.38 ± 0.13 ^{de}	21.81 ± 0.25 ^{ef}	79.24 ± 0.89 ^b
160°C 10min	15.3 ± 0.35 ^g	5.25 ± 0.44 ^{ef}	18.23 ± 0.20 ^f	77.32 ± 1.92 ^d
160°C 20min	14.24 ± 0.32 ^h	5.27 ± 0.56 ^{ef}	17.53 ± 0.22 ^{fg}	75.87 ± 1.51 ^e
160°C 30min	13.13 ± 0.29 ⁱ	5.21 ± 0.33 ^f	16.17 ± 0.18 ^g	72.51 ± 0.49 ^g

Values are expressed as mean ± SD (n = 3). Different superscript letters within the same column indicate significant differences at p < 0.05 (one-way ANOVA followed by Tukey's HSD test).

2.8. Color Analysis

Roasting temperature and duration significantly affected all color parameters of bee pollen (p < 0.05) are shown in Table 3. The color a* value increased significantly with increasing roasting severity, indicating a progressive shift toward red–brown coloration. This trend corresponds with the observed reduction in total sugar and protein contents reported previously. As roasting intensity increased, reducing sugars and amino acids increasingly participated in Maillard reactions, producing brown-colored melanoidin pigments that contribute to higher a* values [36]. Conversely, color b* values decreased significantly with increasing temperature and time, indicating a loss of yellow chromaticity. This decrease is associated with the degradation of native pigments and their transformation into darker compounds during advanced Maillard reactions and caramelization processes [33]. The statistical separation among treatments confirms that b* is highly sensitive to roasting intensity. Color lightness (L*) showed a significant decline from mild to severe roasting conditions, reflecting progressive darkening of the sample. The reduction in L* closely parallels the decrease in total sugar and protein contents, supporting the role of non-enzymatic browning reactions in color development. Samples roasted at 120–160°C exhibited significantly lower L* values compared to those roasted at 80°C, indicating more advanced thermal reactions [24, 36–37]. Similarly, the hue angle (h°) decreased significantly with increasing roasting severity, demonstrating a shift from yellowish tones toward reddish-brown hues. This shift is consistent with the formation of Maillard reaction products and

polymerized melanoidins, which dominate color characteristics at higher roasting temperatures [37-41]. The strong statistical separation of hue angle values highlights its suitability as an indicator of roasting progression. Overall, Tukey HSD analysis confirms that color development during roasting is strongly linked to the degradation of sugars and proteins through Maillard reactions [31-32]. The coordinated changes in a^* , b^* , L^* , and hue angle provide clear visual evidence of chemical transformations occurring during roasting, reinforcing the role of color parameters as reliable indicators of both roasting intensity and nutritional modification in bee pollen.

Table 3. Effect of Roasting Temperature on Color Parameters (L , a , b^* , and Hue angle) of *H. itama* Bee Pollen

Roasting Condition	Color a^*	Color b^*	Color L^*	Hue $^\circ$
80°C 10min	5.51 ± 0.43 ⁱ	18.12 ± 0.54 ^a	65.3 ± 0.82 ^a	73.0 ± 0.78 ^a
80°C 20min	6.29 ± 0.19 ^h	17.66 ± 0.22 ^b	63.7 ± 0.62 ^b	70.6 ± 0.84 ^b
80°C 30min	6.99 ± 0.08 ^g	16.82 ± 0.45 ^c	62.1 ± 0.55 ^c	67.7 ± 0.98 ^c
120°C 10min	7.76 ± 0.27 ^f	16.65 ± 0.23 ^{cd}	60.5 ± 0.72 ^d	65.4 ± 0.77 ^d
120°C 20min	8.67 ± 0.16 ^e	16.03 ± 0.26 ^d	58.9 ± 0.62 ^e	61.7 ± 0.46 ^e
120°C 30min	9.11 ± 0.08 ^d	15.49 ± 0.34 ^e	57.2 ± 0.84 ^f	59.2 ± 0.55 ^f
160°C 10min	9.74 ± 0.39 ^c	14.84 ± 0.34 ^f	55.4 ± 0.95 ^g	56.7 ± 0.69 ^g
160°C 20min	10.35 ± 0.19 ^b	14.31 ± 0.36 ^g	53.7 ± 0.77 ^h	54.4 ± 0.73 ^h
160°C 30min	10.7 ± 0.16 ^a	13.86 ± 0.09 ^h	52.1 ± 0.66 ⁱ	52.2 ± 0.92 ⁱ

Values are expressed as mean ± SD (n = 3). Different superscript letters within the same column indicate significant differences at $p < 0.05$ (one-way ANOVA followed by Tukey's HSD test).

Conclusion

Roasting temperature and duration significantly affected the physicochemical, nutritional, functional, and color properties of bee pollen. Increasing roasting severity reduced moisture, ash, protein, fat, total sugar, pH, and vitamin C contents, indicating progressive thermal degradation and intensified Maillard reactions. In contrast, carbohydrate content increased due to the relative concentration effect associated with the loss of other macronutrients. Moderate roasting conditions improved solubility, with the highest value observed at 120°C for 20 min, whereas excessive roasting reduced solubility, likely due to macromolecular aggregation and formation of insoluble Maillard products. Color changes, characterized by increased redness and reduced lightness and hue angle, closely reflected the degradation of sugars and proteins and the formation of browning pigments. Overall, mild to moderate roasting conditions (80–120°C, ≤20 min) offered an optimal balance between nutrient retention, functional performance, and controlled color development, supporting their application in functional food processing of bee pollen.

The authors gratefully acknowledge the financial support from the Ministry of Higher Education, Science, and Technology of Indonesia through the Research Grant Scheme No.10/PL21.G/PG/2025. The authors also extend their appreciation to the Institute for Research and Community Service (LP2M) of the Samarinda State Agricultural Polytechnic for its administrative assistance. Special thanks are due to the research team, students, and field collaborators for their valuable contributions during sample collection and analysis of *H. itama* bee pollen from East Kalimantan.

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