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Effects of Foil Pouch and PET Jar on the Storage Properties of Spray-Dried *Kelulut* Honey Powder

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Abstract *Kelulut* honey, derived from stingless bees, possesses valuable nutritional and bioactive properties but presents challenges in terms of storage stability and transportability in its natural liquid form. This study aimed to produce spray-dried *kelulut* honey powder using maltodextrin as a carrier agent and to evaluate its physicochemical properties and stability during storage in two alternative packaging materials: metallized aluminium foil (MAF) pouches and polyethylene terephthalate (PET) jars. The exploration of these packaging options provides additional insight into practical, travel-friendly alternatives to conventional glass containers. The honey powder achieved a high yield of $51.19 \pm 1.52\%$ and initially exhibited low moisture content and water activity, which are critical for preventing microbial growth and extending shelf life. During 48 days of storage, MAF pouches outperformed PET jars in maintaining product quality, as evidenced by significantly lower moisture uptake, reduced caking, and more consistent water activity and bulk density values ($p < 0.05$). Both packaging types retained the powder's pH, total phenolic content, and antioxidant activity, with a notable increase in phenolic compounds over time, suggesting enhanced bioavailability. Color changes were more pronounced in PET jars. The water solubility index remained above 90% throughout storage, confirming the powder's functional applicability in food systems. Despite limitations associated with the use of high-temperature spray drying, the honey powder retained its essential functional properties. This study demonstrates the feasibility of converting *kelulut* honey into a shelf-stable powder suitable for convenient storage, transportation, and application in food formulations. The findings contribute to the growing body of knowledge on honey powder development and highlight the relevance of packaging material selection in preserving product quality. The results support the commercialization of portable honey-based products, while also enhancing the economic value of locally produced stingless bee honey and promoting its wider adoption in health-oriented markets.

Keywords Stingless Bee, *Kelulut*, Honey Powder, Spray Drying, Foil Pouch, PET Jar, Storage

1. Introduction

Honey has long been valued for its therapeutic and nutritional benefits, making it a widely recognized natural food product [1]. It is a complex mixture primarily composed of sugars, along with other bioactive compounds derived from nectar or honeydew through the enzymatic activity of bees [2]. The honey produced by *Apis mellifera* (commonly known as the honeybee) has gained global commercial significance due to its well-documented health benefits [3]. In addition to *Apis mellifera*, stingless bees, classified within the *Meliponini* tribe of the Apidae family, also produce honey. This honey, known as stingless bee honey, is referred to as *kelulut* honey in Malaysia [4,5]. Unlike honeybee honey, *kelulut* honey is characterized by

its higher moisture content, distinct taste profile, and unique physicochemical properties influenced by factors such as floral sources, bee species, geographical location, and environmental conditions [6,7]. During honey production, stingless bees modify collected nectar through enzymatic processes, introducing organic compounds that contribute to its distinctive flavor, acidity, and medicinal properties [8,9]. Extensive research has highlighted *kelulut* honey's therapeutic attributes, including its antioxidant, antibacterial, and anti-inflammatory properties, distinguishing it from *Apis mellifera* honey [10,11].

Despite its growing popularity, the natural liquid form of *kelulut* honey poses challenges for large-scale production and consumption due to its high viscosity and tendency to crystallize [12]. This crystallization, driven by its high glucose content, can complicate handling, packaging, and pouring processes, affecting both industrial applications and consumer perception [8,13]. Additionally, the honey's high moisture content makes it susceptible to fermentation, which can compromise its quality and shelf life [8,14,15].

To overcome these limitations, converting *kelulut* honey into a powdered form through dehydration presents a viable solution. Honey powder offers several advantages, including extended shelf life, ease of handling, improved flowability, and reduced risk of crystallisation or fermentation [16]. Furthermore, powdered honey is more convenient for food formulation, as it can be easily incorporated into dry mixes, coatings, and seasonings while also reducing transportation costs and minimizing product loss due to stickiness [12,17].

Based on the literature, spray drying studies on honey have consistently highlighted the importance of selecting appropriate carriers and inlet drying temperatures to produce stable powders. Carriers such as maltodextrin, dextrin, gum Arabic, rice protein, and whey protein are commonly incorporated to reduce stickiness, limit hygroscopicity, and prevent caramelization during drying. Reported inlet temperatures typically range between 150 °C and 200 °C, while optimal carrier-to-honey ratios are emphasized to improve flowability, enhance powder yield, and preserve product quality. These findings formed the scientific basis for determining the inlet drying temperature and honey-to-carrier ratio evaluated in the present study.

Several studies have been conducted on honeybee honey. Nurhadi et al. [18] spray-dried *Perhutani* honey from Bandung, Indonesia, at 180 °C with a filler-to-honey ratio of 50:50. Similarly, Samborska et al. [19] processed Polish multifloral and buckwheat honeys at 180 °C using gum Arabic as a carrier, with or without sodium caseinate, preparing feed solutions at 30% w/w solids and a 50:50 honey-to-carrier solids ratio, with additional 1 to 2% w/w sodium caseinate. Suhag and Nanda [20] obtained nutritionally rich powders from *Helianthus annuus* honey when it was spray-dried at 170 °C with 45% gum Arabic combined with aonla and basil extracts. Lakshmi et al. [21] also produced powders from honeybee honey with maltodextrin and tri-calcium phosphate as an anti-caking agent across drying temperatures of 180 to 200 °C, using a honey-to-maltodextrin-to-water ratio of 1:1:3. Likewise, Suhag et al. [22] diluted *Helianthus annuus* honey with water (1:3.5) and incorporated gum Arabic (45%), maltodextrin (50%), and whey protein concentrate (35%), enabling successful spray drying at 170 °C. Jedlińska et al. [23] further compared conventional spray drying at 180 °C with dehumidified-air drying at 75 °C for rapeseed and honeydew honeys, showing that the lower-temperature method preserved more polyphenols, aromatic compounds, and antioxidant activity, although aroma loss remained a sensory challenge. More recently, Toniazzo et al. [24] developed powders from Rowse honey (Ethiopian honey) using isolated rice protein, pea protein, or their blends as carriers at an average inlet temperature of 130 °C, with a honey-to-carrier ratio of approximately 1:1.

For stingless bee honey, Cuevas-Glory et al. [25] reported optimal conditions at 150 °C and 61% maltodextrin, achieving a 40% powder yield and 71% volatile retention. Building on this, Leyva-Moguel et al. [26] applied the same approach to *Scaptotrigona pectoralis* honey, producing powders with high volatile retention (77%) and enhanced antioxidant activity compared with liquid honey. Overall, the body of research on honeybee honey is more extensive and well-documented, whereas studies on stingless bee honey remain limited, particularly in producing powder from stingless bee honey and optimizing its stability and functional quality.

Previous studies have demonstrated that honey powder retains favorable flow properties and low cohesiveness when stored at 20 °C for up to 12 weeks [19]. Storage at 25 °C (room temperature) is generally preferable, as higher temperatures tend to accelerate degradation processes [27]. However, most spray-drying research on honey powder has primarily concentrated on production parameters and immediate physicochemical characterization, with limited emphasis on systematic storage evaluation. In particular, the influence of packaging materials on maintaining the stability of honey powder at room temperature conditions has not been comprehensively examined. The present study therefore addresses this gap by investigating storage stability in detail, specifically through a comparative assessment of food-grade metallized aluminum foil (MAF) pouches and amber polyethylene terephthalate (PET) jars, to determine which packaging material more effectively preserves the quality of honey powder during storage at room temperature.

2. Materials and Methods

2.1. Chemicals

All the chemicals used were of analytical or high-performance liquid chromatography (HPLC) grade.

Analytical standards and related chemicals were purchased from reputable dealers or suppliers. The maltodextrin was used as a bulking agent or carrier material.

2.2. Samples Collection

The *kelulut* honey used in this project was sourced from a local bee farm. Upon receipt, all the honey samples were stored at 4 °C until further analysis.

2.3. Preparation of Spray-Dried Honey Powder

Honey powder was produced using the spray drying technique. Preliminary observations showed that a honey-to-filler (maltodextrin) ratio of 2:1 resulted in a mixture with viscosity too high to be pumped into the spray dryer, making it impractical for processing. Conversely, a 1:2 honey-to-maltodextrin ratio contained an excessive amount of filler, leading to a noticeably reduced honey content. Based on these initial trials, a 1:1 ratio of honey-to-maltodextrin with 20% dry basis (w/w) was selected, as it provided manageable viscosity during preparation and spray drying while retaining a honey-rich final product.

Prior to drying, raw liquid honey and maltodextrin were mixed in a 1:1 mass ratio and dissolved in distilled water. The mixture was homogenized using a magnetic stirrer to ensure uniform consistency. Spray drying was performed using a laboratory-scale atomiser spray dryer (SD-Basic Spray Dryer, LabPlant, UK) operated at feed flow rate of 12.5 mL/min. An inlet temperature of 180 °C was applied, as this is the minimum inlet temperature required for this unit of spray dryer to achieve proper atomization and powder formation. In addition, comparative trials showed that operating at 180 °C with a 1:1 honey-to-maltodextrin ratio produced powders with better retention of phenolic compounds than those obtained at 200°C. Therefore, an inlet temperature of 180 °C was selected for subsequent experiments to ensure functional quality while reducing processing costs. Once the set temperature was reached, the feed solution was pumped into the drying chamber, atomized, and subsequently dried. The resulting honey powder was collected from the cyclone separator attached to the spray dryer.

2.4. Packaging and Storage of Honey Powder

After cooling to room temperature, the powder was individually packaged in food-grade metallized aluminum foil (MAF) pouches and amber polyethylene terephthalate (PET) jars. Both packaging materials were procured from online vendors, and their dimensions were measured. The thickness of the MAF pouches was obtained from the supplier. The PET jars were thoroughly cleaned with tap water, air-dried, and subsequently decontaminated under UV light (15 W) in a laminar flow cabinet (Solab, SLH-656/4, New York, NY, USA) for 15 min.

Each MAF pouch was filled with 15 g of spray-dried honey powder and heat-sealed, ensuring minimal residual air without vacuum application. An equal amount of powder was placed in PET jars, which were sealed manually by screwing on the PET caps. The condition of the sealed pouches was visually inspected to confirm the absence of potential leakage. The packaged powder samples were stored at ambient conditions (30 ± 2 °C and 50 ± 2% relative humidity). During storage, the PET jars and MAF pouches were positioned vertically to maintain uniform exposure to environmental conditions. Powder properties were monitored periodically, and all analyses were conducted in triplicate using different batches of spray-dried honey powder to ensure reproducibility.

2.5. Assessment of Powder Properties

2.5.1. Powder Yield

The powder yield was determined as the ratio of the mass of solids collected after spray drying to the mass in the feed solution on a dry basis, as shown in (1). The powder yield was expressed in percentage (%).

$$\text{Powder yield} = \frac{\text{Weight of dry powder (g)}}{\text{Total solids of the solution (°Bx)}} \times 100\% \quad (1)$$

2.5.2. Moisture Content

The moisture content was determined gravimetrically by drying the 2 g powder samples in a vacuum oven at 70 °C and −0.090 MPa until the constant weight was obtained [28].

2.5.3. Water Activity

The water activity (a_w) of the samples was measured using a water activity analyzer (Aqua Lab Dew Point Water Activity Meter 4TE, USA) based on the chilled mirror dew point method [29]. A 1.2 g powder sample was evenly distributed on a sample dish, placed in the instrument chamber, and securely sealed. Upon completion of the analysis, the measured water activity (ranging from 0 to 1) and the analysis temperature (25 °C) were displayed on the screen.

2.5.4. pH

The dried honey powder was reconstituted in water to prepare a 20% w/v solution, selected to approximate the sweetness of typical honey-based beverages or products. The pH of the reconstituted solution was then measured using a benchtop digital pH meter (Sartorius, Germany).

2.5.5. Color Measurement

The color of the powder samples was measured using a chromameter (CR-400, Konica Minolta Sensing, Japan) in the CIE *L*a*b** color space, following the method described by Gonzales et al. [30]. The instrument was first calibrated using a white calibration plate prior to

measurements. The chromameter was then set to $L^*a^*b^*$ mode, where color was quantified using three parameters: L^* (lightness), ranging from 0 (black) to 100 (white); a^* (chromaticity), with positive values indicating red and negative values indicating green; and b^* (chromaticity), with positive values indicating yellow and negative values indicating blue. The total color difference (ΔE^*) between fresh *kelulut* honey powder and stored powder was calculated using (2).

$$\Delta E^* = \sqrt{(L_t^* - L_0^*)^2 + (a_t^* - a_0^*)^2 + (b_t^* - b_0^*)^2} \quad (2)$$

The suffixes 't' and '0′ denote the indices of powder on t^{th} day of storage and freshly prepared powder on 0^{th} day, respectively, for lightness (L^*), redness (a^*), and yellowness (b^*).

The Chroma (C^*) and Hue (H) of the samples were calculated using (3) and (4), respectively.

$$C^* = (a^{*2} + b^{*2})^{1/2} \quad (3)$$

$$H = \tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (4)$$

2.5.6. Total Phenolic Content

The total phenolic content (TPC) of spray-dried honey powder was determined using the Folin-Ciocalteu method [31], with slight modifications. A 1 mL aliquot of the reconstituted honey solution was mixed with 5 mL of 0.2 N Folin-Ciocalteu reagent and incubated for 5 min. Subsequently, 4 mL of 7.5% sodium carbonate (Na_2CO_3) solution was added, and the mixture was incubated in the dark at room temperature for 2 h to allow the reaction to proceed. The absorbance was then measured at 765 nm using a UV-Vis spectrophotometer (Cary 60 UV-Vis, Agilent Technologies, USA). A standard calibration curve for TPC was constructed using gallic acid at concentrations ranging from 20 to 100 ppm. The total phenolic content was expressed as mg of gallic acid equivalent (GAE) per liter of honey solution.

2.5.7. Determination of Antioxidant Capacity

The free radical scavenging activity of the reconstituted honey solution (20% w/v) was evaluated using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay [32], with slight modifications. A 1 mL aliquot of the honey solution was mixed with 5400 µL of DPPH solution (6×10^{-5} mol/L) in a centrifuge tube. Methanol (3 mL) was used as the reference (zero absorbance), while a blank was prepared by replacing the honey solution with methanol and mixing it with 5400 µL of DPPH solution. The mixture was homogenised using a vortex mixer at 1000 rpm for 30 seconds and then incubated in the dark for 15 min. Following incubation, the sample was centrifuged at 4500 rpm for 5 min in a refrigerated centrifuge. The supernatant was collected, and its absorbance was measured at 517 nm using a UV-Vis spectrophotometer (Cary 60 UV-Vis, Agilent Technologies, USA). The radical scavenging activity was expressed as the percentage of DPPH discoloration, calculated using (5).

$$\text{Antioxidant scavenging activity (\%)} = \frac{A_c - A_s}{A_c} \times 100\% \quad (5)$$

where, A_c is the absorbance of control and A_s is the absorbance of standard or sample.

2.5.8. Loose Bulk Density (DB) & Tapped Density (DT)

A 2 g sample of honey powder was carefully transferred into an empty graduated measuring cylinder and tapped approximately 20 to 25 times [22]. The volume occupied by the powder was then recorded, and the bulk density (DB) was calculated as the mass-to-volume ratio.

To determine the tapped density, the same cylinder was further tapped approximately 120 times, after which the final volume of the powder was recorded [33]. Similar to bulk density, tapped density was calculated by dividing the powder mass by the volume occupied after 120 taps.

2.5.9. Water Solubility Index

The water solubility index (WSI) was determined following the method of Loo and Pui [34], with slight modifications. A 1 g sample of honey powder was mixed with 10 mL of distilled water and incubated in a water bath at 37 °C for 30 min. The mixture was then centrifuged for 10 min, and the supernatant was collected and oven-dried at 105 °C until a constant weight was achieved. The WSI was calculated using (6).

$$\text{Water solubility index} = \frac{\text{Weight of dried powder}}{\text{Weight of original powder}} \times 100\% \quad (6)$$

2.5.10. Degree of Caking

The degree of caking was assessed using the method described by Ramachandra and Rao [35]. A 5 g sample of powder was placed in a sieve with a 500 µm mesh size and shaken rigorously until no further powder passed through. The weight of the remaining powder on the sieve was then measured and recorded. The degree of caking was calculated using (7).

$$\text{Degree of caking} = \frac{c}{d} \times 100 \quad (7)$$

where, d (g) denotes the amount of powder used for sieving, and c (g) is the amount of powder left on the sieve after sieving.

2.6. Water Vapour Permeability of Packaging Materials

The water vapor permeability of the packaging materials was determined following the method of Devi et al. [36], with slight modifications. Five grams of dehydrated silica gel were individually sealed in the food-grade metallized aluminum foil (MAF) pouches, and amber polyethylene terephthalate (PET) jars. The packaged samples were then placed in a humidity chamber maintained at 90% relative

humidity and 36 ± 2 °C. The mass of each package containing silica gel was recorded at 24-h intervals over eight days, and the average daily weight increase of the silica gel was calculated [36,37]. The water vapor permeability (K, kg/m²/day/Pa) of the MAF pouches, and amber PET jars was determined using (8).

$$K = \frac{dw/d\theta_p}{A_p p*} \quad (8)$$

where, $(dw/d\theta_p)$ (kg/day) is the slope of the linear plot between the time θ_p (day) of incubation and cumulative moisture gain, w (kg) is the weight of silica gel in the packaging material, A_p (m^2) is the surface area of the packaging material and $p*$ is the saturation pressure (Pa) of the water at 36 °C i.e., the temperature of the environment during the experiment.

2.7. Statistical Analysis

All analyses were conducted in triplicate, and the results were expressed as mean ± standard deviation. IBM SPSS Statistics for Windows, Version 23 (IBM Corp., NY, USA) was used for statistical analysis. Experimental results were subjected to t-test (two time points) or one-way analysis of variance (more than two time points). The significant differences among means at 95% confidence limits ($p < 0.05$) were determined by Tukey's test.

3. Results and Discussion

3.1. Powder Yield

The yield of *kelulut* honey powder obtained in this study, ranges from 48.69% to 52.67%, with an average yield of 51.19 ± 1.52% at a 50:50 honey-to-maltodextrin ratio. This yield is significantly higher than the 9.7% reported by Nurhadi et al. [18] under the same formulation. Additionally, the obtained yield is comparable to the 52.8% reported by Shi et al. [28] using a 40:60 honey-to-maltodextrin ratio, suggesting that the spray drying conditions in the present study effectively enhanced powder recovery.

3.2. Analysis of Honey Powder Properties

3.2.1. Moisture Content and Water Activity

Table 1 presents the changes in moisture content of *kelulut* honey powder stored in MAF pouches and PET jars. A statistically significant difference ($p < 0.05$) was observed between the two packaging materials. The moisture content in both storage conditions increased progressively from day 0 to day 35, after which it stabilized. However, by day 48, the moisture content in PET jars could no longer be accurately measured due to caking, which hindered precise assessment. The hygroscopic nature of honey powder makes it highly susceptible to moisture absorption, leading to caking. This phenomenon occurs due to moisture migration within sealed containers, resulting in particle agglomeration and solidification. The initial moisture content of *kelulut* honey powder (day 0) aligns with the findings of Nurhadi et al. [18], who reported moisture content of 2.3% for spray-dried honey powder with maltodextrin as an anticaking agent.

Throughout the storage period, PET jars exhibited higher moisture content than MAF pouches, likely due to their lower water vapor permeability, as indicated in Table 2. The permeability values (K) differed significantly ($p < 0.05$) between the two packaging materials, with lower values indicating superior moisture barrier properties. MAF pouches demonstrated higher permeability, facilitating greater moisture exchange due to their polymer-based composition [38]. These permeability differences correspond with the observed trends in moisture regulation for each packaging type. In the present study, the use of metallisd aluminum foil (MAF) pouches and amber polyethylene terephthalate (PET) jars was intended to explore alternative packaging options to glass bottles, with the aim of enhancing portability and convenience, particularly for travel and on-the-go use.

Table 1. Moisture content and water activity of *kelulut* honey powder within two packaging types

Storage Period (Day)	Moisture content (%)		Water activity (a_w)	
	MAF	PET	MAF	PET
0	$2.79 \pm 0.06^{a,A}$	$2.63 \pm 0.09^{a,B}$	$0.36 \pm 0.02^{b,A}$	$0.36 \pm 0.00^{ab,A}$
21	$3.60 \pm 0.47^{ab,A}$	$3.76 \pm 0.34^{ab,A}$	$0.33 \pm 0.01^{a,A}$	$0.32 \pm 0.01^{a,A}$
35	$4.03 \pm 0.55^{b,A}$	$4.46 \pm 0.31^{c,A}$	$0.36 \pm 0.01^{ab,A}$	$0.37 \pm 0.02^{bc,A}$
40	$3.76 \pm 0.04^{b,A}$	$4.18 \pm 0.13^{bc,B}$	$0.33 \pm 0.01^{ab,A}$	$0.36 \pm 0.02^{b,B}$
44	$3.88 \pm 0.04^{b,A}$	$4.39 \pm 0.19^{bc,B}$	$0.36 \pm 0.01^{ab,A}$	$0.40 \pm 0.02^{c,B}$
48	3.98 ± 0.13^{b}	$^{\#}$ND	0.36 ± 0.01^{b}	$^{\#}$ND

$^{a-c}$Values in the same column with different lowercase letters denote significant differences ($p < 0.05$) for a given packaging material across different storage durations. $^{A-B}$Values in the same row with different uppercase letters of the same parameter indicate significant differences ($p < 0.05$) between packaging materials at the same storage duration. $^{\#}$ND: Not detectable.

Table 2. Water vapour permeability of packaging materials

Types of Packaging Materials	Water Vapour Permeability, *K* ($\times 10^{-7}$ kg/m^2/day/Pa)
PET Jar	1.61 ± 0.00^{a}
MAF Pouch	3.50 ± 0.00^{b}

[a-b]Values in the same column with different lowercase letters denote significant differences ($p < 0.05$) in water vapour permeability values among different packaging materials.

Jaime et al. [39] conducted a comparative study on glass, polyethylene terephthalate (PET), and high-density polyethylene (HDPE) bottles, demonstrating that the non-porous structure of glass provides the most effective barrier against moisture and oxygen. In contrast, the molecular composition and partially crystalline structures of PET and HDPE contribute to their higher permeability. This increased permeability results from the incomplete crystallization of polymers, which creates variations in their ability to resist moisture and gas penetration, depending on molecular configuration and material thickness. While PET exhibits excellent gas barrier properties and high mechanical strength, its effectiveness in preventing moisture infiltration remains limited. The authors [39] also reported that PET and HDPE bottles exhibited increased WVTR at 40 °C and 75% RH, while permeability decreased at 23 °C under the same RH conditions. In contrast, glass bottles showed minimal changes in permeability across varying storage environments.

Water activity of honey powder stored in MAF pouches initially decreased by day 21, remained stable, and showed a slight increase toward the end of the storage period (Table 1). Conversely, samples in PET jars exhibited an initial decline in water activity followed by a substantial increase in later storage stages. Ultimately, water activity in PET jars became undetectable due to caking. These results suggest that MAF pouches provide better moisture barrier properties compared to PET jars, as evidenced by statistically significant differences ($p < 0.05$) between the two packaging types. The more consistent water activity in MAF pouches may be attributed to their higher water vapour permeability than PET jars, which facilitates controlled moisture exchange and maintains a stable equilibrium between the honey powder and the external environment.

Water activity (a_w) reflects the availability of water in dry materials and its ability to function as a solvent, participate in biochemical reactions, and support microbial growth [40]. In contrast, moisture content refers to the total water present in a food product, typically expressed as a percentage by weight on a wet basis. The relationship between water activity and moisture content is described by the moisture sorption isotherm, which varies depending on the food matrix, temperature, and humidity conditions [41]. The addition of maltodextrin as a carrier agent has been shown to enhance solubility and reduce moisture content in spray-dried honey powders, contributing to lower water activity levels. This aligns with the findings of the present study, where the low water activity of *kelulut* honey powder suggests effective moisture reduction, likely facilitated by maltodextrin incorporation. Suhag et al. [22] reported that maltodextrin effectively reduces moisture content while improving the overall quality of honey powder. Similarly, Keke and Cinkmanis [42] demonstrated that using dehumidified air during spray drying results in honey powders with lower water activity, thereby enhancing stability.

3.2.2. pH

Throughout the storage period, the pH of *kelulut* honey powder exhibited minimal fluctuations, irrespective of the packaging material used (Table 3). This stability suggests that the honey powder's acidity remains largely unaffected by storage duration or packaging conditions, demonstrating its resistance to environmental influences.

Table 3. Changes in pH of *kelulut* honey powder

Storage Period (Day)	pH	
	MAF	PET
0	$3.16 \pm 0.01^{a,B}$	$3.14 \pm 0.01^{a,A}$
21	$3.20 \pm 0.01^{b,A}$	$3.22 \pm 0.00^{b,B}$
35	$3.21 \pm 0.01^{b,A}$	$3.25 \pm 0.01^{c,B}$
40	$3.23 \pm 0.01^{c,A}$	$3.25 \pm 0.00^{c,B}$
44	$3.23 \pm 0.01^{c,A}$	$3.26 \pm 0.00^{c,B}$
48	$3.23 \pm 0.01^{c,B}$	$3.22 \pm 0.01^{b,A}$

[a-c]Values in the same column with different lowercase letters denote significant differences ($p < 0.05$) for a given packaging material across different storage durations. [A-B]Values in the same row with different uppercase letters indicate significant differences ($p < 0.05$) between packaging materials at the same storage duration.

Statistical analysis revealed significant differences ($p < 0.05$) in the pH values of *kelulut* honey powder over time and between packaging materials. The pH of honey powder stored in MAF pouches increased slightly from 3.16 ± 0.01 on day 0 to 3.23 ± 0.01 on day 48. In contrast, samples stored in PET jars exhibited an initial rise from 3.14 ± 0.01 on day 0 to a peak of 3.26 ± 0.00 on day 44, followed by a slight decline to 3.22 ± 0.01 on day 48. These pH values align with those reported by Wongsa et al. [43], where raw *H. itama* honey exhibited acidic pH levels ranging from 3.06 ± 0.01 to 3.32 ± 0.01. Similarly, Keng et al. [44] documented pH values for stingless bee honey ranging from 3.29 to 3.71, with regional variations across Peninsular Malaysia.

3.2.3. Total Phenolic Content

Over the 48-day storage period, TPC in MAF pouches exhibited a steady increase, rising from 71.54 ± 0.70 mg GAE/L on day 0 to 82.81 ± 2.64 mg GAE/L by day 48 (Table 4). Statistical analysis confirmed significant

differences ($p < 0.05$) in TPC across storage days for samples stored in MAF pouches. Similarly, honey powder stored in PET jars displayed an increasing trend, with TPC rising from 71.37 ± 1.24 mg GAE/L on day 0 to 83.20 ± 3.36 mg GAE/L on day 48. However, no statistically significant differences ($p > 0.05$) were observed between storage days for PET jars, indicating a more stable retention of TPC compared to MAF pouches.

The observed increase in total phenolic content (TPC) during storage may be attributed to the release or transformation of bound phenolic compounds into free, bioavailable forms as the honey powder stabilizes. The moderate storage temperature (30 °C) applied in this study likely provided a favorable environment for these gradual transformations while minimizing degradation. In stingless bee honey, phenolic compounds occur either as glycosides bound to sugars or as free aglycones [45]. Prolonged storage can disrupt glycosidic bonds, thereby releasing phenolics into free forms that are more readily detectable, contributing to elevated TPC values. Comparable trends have been observed in other honey varieties, such as Manuka honey, where storage promoted the accumulation of specific phenolic compounds and enhanced antioxidant capacity [46].

Phenolic compounds are key contributors to antioxidant activity, primarily through hydrogen atom donation from hydroxyl groups that neutralize free radicals. Thus, antioxidant potential is closely linked to both the number and stability of hydroxyl groups [47]. In honey, flavonoids and phenolic acids may remain stable or even increase in concentration during storage, as they are progressively released from the matrix [46,48]. Their stability, however, is strongly influenced by moisture content, a critical determinant of food powder quality. Elevated moisture accelerates microbial activity and hydrolytic reactions, leading to phenolic degradation, whereas consistently low moisture generally favours stability [49]. In the present study, the honey powder maintained a low moisture level throughout storage, a condition that likely supported both the preservation and gradual release of phenolic compounds by reducing susceptibility to hydrolytic and microbial degradation.

Furthermore, Ghani et al. [50] reported a positive correlation between increasing TPC and enhanced antioxidant activity, suggesting that storage at constant room temperature can facilitate phenolic release. However, their findings also highlighted that while certain phenolic compounds are liberated upon heating, others undergo degradation. This dual behaviour underscores the complexity of TPC dynamics, where the accumulation of some phenolics may be offset by the loss of others, ultimately shaping the antioxidant profile over time.

3.2.4. Radical Scavenging Activity Using DPPH Assay

Over the 48-day storage period, the antioxidant activity of *kelulut* honey powder exhibited a notable increase in both packaging types (Table 4). Specifically, the antioxidant activity in MAF pouches increased from 35.59 ± 1.25% on day 0 to 46.75 ± 0.39% on day 48, while samples stored in PET jars showed an increase from 37.37 ± 0.62% to 47.00 ± 1.71% over the same period.

The present study assessed the radical scavenging activity of *kelulut* honey powder using the DPPH assay. Antioxidant activity refers to the ability of specific compounds or mixtures to neutralize reactive species or pro-oxidants, including free radicals [43]. A higher percentage of radical scavenging activity indicates a greater antioxidant capacity. This assay is widely employed due to its simplicity, rapid analysis time, and the affordability of spectrophotometric equipment required for the measurement [43].

Table 4. Changes in TPC and antioxidant properties of *kelulut* honey powder

Storage Period (Day)	TPC (mg GAE/L)		Radical scavenging activity (%)	
	MAF	PET	MAF	PET
0	$71.54 \pm 0.70^{a,A}$	$71.37 \pm 1.24^{a,A}$	$35.59 \pm 1.25^{a,A}$	$37.37 \pm 0.62^{a,A}$
21	$74.58 \pm 0.98^{ab,A}$	$72.94 \pm 0.80^{a,A}$	$41.44 \pm 1.21^{b,A}$	$40.03 \pm 0.45^{ab,A}$
35	$76.07 \pm 1.22^{bc,A}$	$74.61 \pm 1.02^{a,A}$	$44.85 \pm 0.49^{cd,B}$	$41.13 \pm 0.27^{bc,A}$
40	$79.14 \pm 0.35^{cd,A}$	$82.86 \pm 3.62^{a,A}$	$43.57 \pm 0.92^{bc,A}$	$42.85 \pm 1.01^{c,A}$
44	$77.61 \pm 1.68^{bc,A}$	$80.11 \pm 9.30^{a,A}$	$44.50 \pm 0.42^{cd,A}$	$42.68 \pm 1.19^{bc,A}$
48	$82.81 \pm 2.64^{d,A}$	$83.20 \pm 3.36^{a,A}$	$46.75 \pm 0.39^{d,A}$	$47.00 \pm 1.71^{d,A}$

[a-d]Values in the same column with different lowercase letters denote significant differences ($p < 0.05$) for a given packaging material across different storage durations. [A-B]Values in the same row with different uppercase letters of the same parameter indicate significant differences ($p < 0.05$) between packaging materials at the same storage duration.

Samborska et al. [51] reported that low-temperature spray drying (inlet/outlet air temperatures of 75/50 °C) using dehumidified air positively influenced the antioxidant activity and aroma of the resulting powder. Similarly, Jedlińska et al. [23] found that honey powders produced via low-temperature spray drying with dehumidified air exhibited higher levels of polyphenols, antioxidant activity, and aromatic compounds compared to powders obtained through conventional high-temperature spray drying using inlet air at 180 °C. In the present study, due to equipment limitations – the laboratory spray dryer had a minimum inlet temperature of 180 °C – and the unavailability of dehumidified air, the spray drying process was conducted using the conventional method. Despite the use of conventional spray drying conditions, the resulting honey powder retained measurable levels of antioxidant activity and total phenolic content. Although the values were lower than those reported in studies employing low-temperature drying with dehumidified air [23,51], the presence of these bioactive compounds indicates that some functional properties of the honey were preserved during processing.

In conclusion, the observed increase in TPC and antioxidant activity of *kelulut* honey powder during storage at room temperature can be attributed to a combination of factors, including chemical transformations, the inherent stability of phenolic compounds, and the influence of storage conditions such as temperature and moisture content. Together, these factors determine the overall stability, quality, and antioxidant potential of the honey powder over time.

3.2.5. Loose Bulk Density and Tapped Density

Table 5 presents the statistically significant differences ($p < 0.05$) observed in both loose bulk density and tapped density of *kelulut* honey powder over the storage period within the same packaging material. A comparison between MAF pouches and PET jars revealed a significant difference ($p < 0.05$) in tapped density at day 0. However, at subsequent time points, no significant differences ($p > 0.05$) were observed between the two packaging materials.

The loose bulk density and tapped density of *kelulut* honey powder increased from day 0 to day 35 in both MAF pouches and PET jars, indicating progressive compaction of powder particles and a reduction in inter-particle voids over time. Beyond day 35, a decline in both density parameters suggests the onset of caking, likely due to void formation within agglomerates, which reduces overall density. Prolonged storage, particularly in PET jars, facilitates moisture redistribution within the powder, promoting agglomeration and the formation of irregular clumps. The formation of these agglomerates increases particle size, introduces voids into the powder structure, reduces packing efficiency, and consequently lowers bulk density [52]. Bulk density is a key parameter influencing the handling, processing, and application of *kelulut* honey powder in various food products. Also referred to as packing density, bulk density is defined as the mass of a powder per unit volume and is typically expressed in units such as kg/m³ or g/cm³ [52]. Loose bulk density, also known as aerated bulk density, represents the mass per unit volume of a powder in its naturally settled state, without external compaction [53]. Several factors, including particle morphology, size distribution, interparticle friction, and cohesion, influence how particles settle and fill voids [53]. In contrast, tapped density measures the mass-to-volume ratio of a powder after mechanical tapping, reflecting its random dense packing state [53].

Loose bulk density is influenced by chemical composition, particle size, moisture content, and processing and storage conditions [28]. An increase in maltodextrin concentration in the feed has been shown to elevate loose bulk density, likely due to greater agglomeration and structural disintegration of powder particles, which reduces overall particle volume [28,54]. Kwapinska and Zbicinski [55] reported that maltodextrin reduces the adhesion of thermoplastic particles. Powders exhibiting adhesive or less free-flowing characteristics tend to have higher loose bulk densities, a trend consistent with previous studies [56,57]. Additionally, lower moisture content is associated with higher loose bulk density, as higher moisture levels promote the formation of incompletely dried, larger agglomerates, which in turn reduce bulk density [28,58].

Table 5. Loose bulk density, tapped density and degree of caking of *kelulut* honey powder

Storage Period (Day)	Loose bulk density (g/cm³)		Tapped density (g/cm³)		Degree of caking (%)	
	MAF	PET	MAF	PET	MAF	PET
0	$0.49 \pm 0.02^{a,A}$	$0.54 \pm 0.04^{a,A}$	$0.52 \pm 0.02^{a,A}$	$0.59 \pm 0.03^{a,B}$	$11.79 \pm 0.01^{a,B}$	$9.80 \pm 0.00^{a,A}$
21	$0.60 \pm 0.02^{bc,A}$	$0.61 \pm 0.02^{b,A}$	$0.66 \pm 0.05^{bc,A}$	$0.66 \pm 0.01^{b,A}$	$33.13 \pm 16.04^{a,A}$	$21.13 \pm 1.15^{a,A}$
35	$0.67 \pm 0.00^{d,A}$	$0.68 \pm 0.03^{c,A}$	$0.71 \pm 0.00^{c,A}$	$0.73 \pm 0.03^{c,A}$	$62.44 \pm 8.32^{b,A}$	$31.39 \pm 22.34^{a,A}$
40	$0.64 \pm 0.02^{cd,A}$	$0.61 \pm 0.02^{b,A}$	$0.68 \pm 0.03^{bc,A}$	$0.65 \pm 0.02^{b,A}$	$72.77 \pm 7.56^{bc,A}$	$70.44 \pm 4.95^{b,A}$
44	$0.61 \pm 0.02^{bc,A}$	$0.58 \pm 0.02^{ab,A}$	$0.65 \pm 0.02^{bc,A}$	$0.61 \pm 0.02^{ab,A}$	$87.64 \pm 6.30^{c,A}$	$94.69 \pm 1.50^{b,A}$
45	0.59 ± 0.00^{b}	$^{\#}$ND	0.63 ± 0.00^{b}	$^{\#}$ND	90.02 ± 4.70^{c}	$^{\#}$ND

$^{a-d}$Values in the same column with different lowercase letters denote significant differences ($p < 0.05$) for a given packaging material across different storage durations. $^{A-B}$Values in the same row with different uppercase letters of the same parameter indicate significant differences ($p < 0.05$) between packaging materials at the same storage duration. $^{\#}$ND: Not detectable.

The choice of drying agent also significantly affects the bulk density of powders. Samborska et al. [57] demonstrated that powders dried using gum Arabic exhibit lower bulk densities than those dried with maltodextrin, even when their compositions are identical. For instance, at a honey-to-drying agent ratio of 1:1, maltodextrin-dried powders exhibited a loose bulk density of 0.55 ± 0.02 g/cm³ and a tapped density of 0.57 ± 0.04 g/cm³, whereas gum Arabic-dried powders showed lower values, with a loose bulk density of 0.32 ± 0.01 g/cm³ and a tapped density of 0.43 ± 0.04 g/cm³.

From a practical perspective, the bulk density of honey powders plays a critical role in transportation and packaging. Higher bulk densities are generally advantageous, as they reduce shipping costs and improve storage efficiency [59]. Furthermore, bulk density significantly influences powder flowability, with lower bulk densities being more susceptible to oxidation and degradation during storage [59].

3.2.6. Degree of Caking

Table 5 also presents the degree of caking in *kelulut* honey powder over the storage period. Statistical analysis revealed a significant increase ($p < 0.05$) in caking for both MAF pouches and PET jars over 48 days, indicating that prolonged storage promotes caking in both packaging materials. The comparable caking behavior observed in both materials suggests a similar susceptibility to this phenomenon.

In the food industry, time-dependent consolidation during storage, commonly referred to as caking, poses a significant challenge for powder handling. According to Hartmann and Palzer [60], caking in amorphous particles initiates with surface stickiness, which can lead to structural collapse. Over time, the bulk powder transitions from a free-flowing state, composed of discrete particles, to a solidified mass. Hartmann and Palzer [60] further noted that powders containing water-soluble amorphous substances are particularly prone to caking due to their ability to absorb moisture. This moisture uptake reduces viscosity, facilitating sintering – a permanent process in which particles adhere to one another, forming rigid lumps.

In the present study, the progressive increase in caking observed in *kelulut* honey powder is likely attributed to its high content of water-soluble amorphous components, such as glucose and fructose. These hygroscopic substances readily absorb moisture, making them highly sensitive to environmental conditions. Additionally, under storage conditions with high relative humidity (50% in the present study), the glass transition temperature (T_g) of these amorphous components may decrease, leading to enhanced particle stickiness, increased adhesion, and the formation of sinter bridges, as described by Hartmann and Palzer [60]. These mechanisms likely explain the rapid onset of caking observed in the present study.

Based on the progression of loose bulk density, tapped density, and particularly the degree of caking (Table 5), the shelf life of the product was primarily limited by deterioration in physical appearance rather than a decline in bioactive properties. Despite showing slower initial caking, PET-packaged samples underwent complete solidification by day 45, rendering them unmeasurable, whereas MAF-packaged samples maintained sufficient physical integrity for analysis throughout the entire storage period. Meanwhile, both total phenolic content and DPPH radical scavenging activity remained relatively stable throughout storage (Table 4), indicating good retention of bioactivity. Notably, no anti-caking agent was incorporated into the formulation, with only a carrier filler added. This likely accelerated caking and ultimately restricted the ability to handle and analyze the product over longer storage durations. Therefore, the estimated shelf life of the product is up to 40 days for PET and at least 45 days for MAF, based on the degree of caking and the point at which physical degradation prevents product analysis and usability.

3.2.7. Water Solubility Index (WSI)

The water solubility index (WSI) of *kelulut* honey powder was assessed over a 48-day period (Table 6). Statistical analysis revealed no significant differences ($p > 0.05$) in WSI values throughout the storage duration for either packaging material. This stability suggests that the controlled humidity and lower temperature effectively preserved the solubility characteristics of the honey powder. The WSI quantifies the extent to which a powder dissolves in water, with higher values indicating greater solubility. A highly soluble powder readily wets, sinks, and disperses in water without forming clumps, which is a critical property for applications in food formulations [61]. The solubility of spray-dried powders, including honey powders, is influenced by both drying conditions and storage environments. Bansal et al. [62] reported that higher drying temperatures lead to lower moisture content and higher WSI values, emphasizing the need to optimize drying parameters to maintain solubility. This is particularly crucial for *kelulut* honey powder, where moisture reduction is essential for preserving its dissolution properties.

Table 6. Water solubility Index, chroma and hue angle of *kelulut* honey powder

Storage Period (Day)	Water solubility index (%)	
	MAF	PET
0	$90.57 \pm 4.19^{a,A}$	$89.38 \pm 0.14^{a,A}$
21	$89.25 \pm 0.46^{a,A}$	$88.87 \pm 0.32^{a,A}$
35	$88.79 \pm 0.23^{a,A}$	$87.59 \pm 1.85^{a,A}$
40	$89.01 \pm 0.09^{a,B}$	$88.50 \pm 0.25^{a,A}$
44	$88.86 \pm 0.27^{a,A}$	$88.09 \pm 0.45^{a,A}$
48	88.12 ± 0.40^{a}	$^{\#}$ND

[a]Values in the same column with different lowercase letters denote significant differences ($p < 0.05$) for a given packaging material across different storage durations. [A-B]Values in the same row with different uppercase letters indicate significant differences ($p < 0.05$) between packaging materials at the same storage duration. [#]ND: Not detectable.

The choice of carrier agents during the spray-drying process also significantly influences the WSI of honey powders. The WSI values observed in the present study at day 0 align with those reported by Lee et al. [63], who found a WSI range of 90.88% to 93.42% in mandarin beverage powder produced with maltodextrin as a carrier. Maltodextrin enhances the solubility of honey powders by providing a structurally favorable matrix for dissolution, as demonstrated in a previous study on spray-dried honey powder [22]. Additionally, maltodextrin reduces powder stickiness and improves handling properties, making it a valuable additive in spray-drying applications [64].

3.2.8. Color Measurement

Color is a critical attribute of food products, as it is the first sensory characteristic perceived by consumers. The CIE $L^*a^*b^*$ system provides a standardized method for quantifying color relationships along three axes: L^* represents lightness, while a^* and b^* correspond to chromaticity. Specifically, the L^* axis ranges from 0 (black) to 100 (white), denoting the degree of lightness. The a^* axis captures variations along the red-green spectrum, with positive values indicating red hues and negative values representing green tones. Similarly, the b^* axis reflects the yellow-blue spectrum, where positive values correspond to yellow shades and negative values indicate blue tones. The total color change (ΔE^*) integrates variations in L^*, a^*, and b^* values, with a ΔE^* exceeding 1.0 considered perceptible to the human eye [65]. Table 7 presents a statistically significant reduction ($p < 0.05$) in the L^* values of *kelulut* honey powder stored in both MAF pouches and PET jars throughout the storage period. In MAF pouches, L^* values declined from 61.12 ± 0.09 on day 0 to 57.51 ± 1.61 by day 21, after which the values stabilized. Similarly, samples stored in PET jars exhibited a more pronounced decline in L^* values, decreasing from 62.16 ± 0.76 at the beginning of storage to 53.38 ± 2.55 at the end of the study.

The reduction in L^* values indicates a progressive darkening of the honey powder, primarily attributed to its high sugar content and hygroscopic nature, which facilitate moisture absorption during storage. The absorbed moisture increases water activity, promoting the Maillard reaction – a non-enzymatic browning process involving the interaction of reducing sugars and amino acids [66]. This reaction leads to the formation of melanoidins, which contribute to the observed color changes and darkening of the honey powder [67]. The decline in L^* values may also be associated with the accumulation of hydroxymethylfurfural (HMF), a degradation product known to cause honey darkening [67]. HMF formation occurs through both the Maillard reaction and thermal degradation of sugars, particularly fructose, under elevated temperatures [68]. The increasing HMF content corresponds to a decrease in L^* values and a shift toward darker hues [69]. In the present study, the recorded a^* and b^* values remained positive throughout the storage period, indicating a reddish and yellowish hue, respectively. Changes in L^* and b^* values align with the browning process, as previously documented by Cui et al. [12].

The total color difference (ΔE^*) of *kelulut* honey powder was significantly influenced ($p < 0.05$) by the type of packaging material, particularly from day 44 onward (Table 8). PET jars exhibited a more pronounced color change compared to MAF pouches, likely due to their black color, which absorbs and retains more heat during storage. This increased heat retention accelerates chemical reactions, including Maillard browning, thereby intensifying color changes. Additionally, the enclosed environment of PET jars may contribute to sustained internal conditions that promote browning reactions. Wong et al. [61] also noted that residual air within packaging can facilitate oxidation, further contributing to color alterations over time.

Table 7. Changes in color parameters of *kelulut* honey powder

Storage Period (Day)	*L**		*a**		*b**	
	MAF	PET	MAF	PET	MAF	PET
0	$61.12\pm0.09^{b,A}$	$62.16\pm0.76^{c,A}$	$0.28\pm0.05^{a,A}$	$0.31\pm0.08^{ab,A}$	$6.62\pm0.22^{a,A}$	$6.44\pm0.12^{a,A}$
21	$57.51\pm1.61^{a,A}$	$58.38\pm1.14^{b,A}$	$0.59\pm0.14^{b,B}$	$0.23\pm0.12^{ab,A}$	$7.28\pm0.22^{a,A}$	$8.38\pm0.39^{b,B}$
35	$56.94\pm0.94^{a,A}$	$57.08\pm0.44^{ab,A}$	$0.19\pm0.14^{a,A}$	$0.29\pm0.04^{ab,A}$	$9.25\pm0.47^{b,A}$	$9.61\pm0.38^{bc,A}$
40	$56.47\pm0.94^{a,A}$	$55.81\pm1.02^{ab,A}$	$0.25\pm0.11^{a,A}$	$0.16\pm0.03^{a,A}$	$9.17\pm0.15^{b,A}$	$10.74\pm0.60^{cd,B}$
44	$56.28\pm0.41^{a,A}$	$53.38\pm2.55^{a,A}$	$0.46\pm0.04^{ab,A}$	$0.37\pm0.05^{b,A}$	$10.65\pm0.38^{c,A}$	$11.35\pm0.66^{d,A}$
48	56.17 ± 0.65^{a}	$^{\#}$ND	0.36 ± 0.12^{ab}	$^{\#}$ND	10.31 ± 0.23^{c}	$^{\#}$ND

$^{a-d}$Values in the same column with different lowercase letters denote significant differences ($p < 0.05$) for a given packaging material across different storage durations. $^{A-B}$Values in the same row with different uppercase letters of the same parameter indicate significant differences ($p < 0.05$) between packaging materials at the same storage duration. $^{\#}$ND: Not detectable.

Table 8. Chroma, hue angle and total color difference (ΔE^*) of *kelulut* honey powder

Storage Period (Day)	Chroma (C^*)		Hue angle (°)		Total color difference (ΔE^*)	
	MAF	PET	MAF	PET	MAF	PET
0	$6.63 \pm 0.22^{a,A}$	$6.44 \pm 0.12^{a,A}$	$87.61 \pm 0.37^{b,A}$	$87.22 \pm 0.69^{a,A}$	0.00	0.00
21	$7.31 \pm 0.21^{a,A}$	$8.38 \pm 0.39^{b,B}$	$85.38 \pm 1.18^{a,A}$	$88.45 \pm 0.75^{ab,B}$	$3.69 \pm 1.52^{a,A}$	$4.29 \pm 0.90^{a,A}$
35	$9.26 \pm 0.47^{b,A}$	$9.61 \pm 0.38^{bc,A}$	$88.85 \pm 0.82^{b,A}$	$88.29 \pm 0.28^{ab,A}$	$5.00 \pm 0.71^{ab,A}$	$6.01 \pm 0.30^{a,A}$
40	$9.17 \pm 0.14^{b,A}$	$10.74 \pm 0.60^{cd,B}$	$88.46 \pm 0.67^{b,A}$	$89.15 \pm 0.12^{b,A}$	$5.33 \pm 0.78^{ab,A}$	$7.69 \pm 1.69^{ab,A}$
44	$10.66 \pm 0.38^{c,A}$	$11.35 \pm 0.66^{d,A}$	$87.55 \pm 0.14^{b,A}$	$88.12 \pm 0.39^{ab,A}$	$6.30 \pm 0.49^{b,A}$	$10.06 \pm 2.25^{b,B}$
48	10.32 ± 0.23^{c}	$^{\#}$ND	88.00 ± 0.63^{b}	$^{\#}$ND	6.19 ± 0.64^{b}	$^{\#}$ND

$^{a-d}$Values in the same column with different lowercase letters denote significant differences ($p < 0.05$) for a given packaging material across different storage durations. $^{A-B}$Values in the same row with different uppercase letters of the same parameter indicate significant differences ($p < 0.05$) between packaging materials at the same storage duration. $^{\#}$ND: Not detectable.

The chroma (C^*) and hue (H) values of the *kelulut* honey powder samples, presented in Table 8, provide a detailed evaluation of their color characteristics. Chroma (C^*) represents color saturation, with higher values indicating greater color intensity. It is determined by the radial distance from the neutral (achromatic) center in the color space [70]. Hue (H) is expressed as an angular measurement along the chromaticity plane, with specific angles corresponding to different color perceptions: 0° (red-purple), 90° (yellow), 180° (bluish-green), and 270° (blue). As shown in Table 8, the C^* values of *kelulut* honey powder increased significantly ($p < 0.05$) over the storage period for both packaging materials, indicating an enhancement in color saturation. The hue values remained stable throughout storage, consistently aligning near 90°, which corresponds to a yellow hue in the CIE $L^*a^*b^*$ color space. This stability suggests that while the honey powder darkened, its predominant yellowish appearance was maintained.

4. Conclusions

The findings of this study demonstrate that packaging material exerts a significant influence on the storage stability of spray-dried *kelulut* honey powder. Both metallized aluminium foil (MAF) pouches and amber polyethylene terephthalate (PET) jars impacted key physicochemical attributes, including moisture content, color parameters, and caking tendency. While PET packaging exhibited better resistance to caking in the early stages of storage, MAF provided superior long-term structural stability, with samples remaining physically measurable through day 45, in contrast to complete solidification observed in PET samples by day 45. Throughout the storage duration, the total phenolic content and DPPH radical scavenging activity remained relatively stable, indicating the effective retention of bioactive compounds irrespective of the packaging type. Based on the degree of physical deterioration, the estimated shelf life is up to 40 days for PET and at least 45 days for MAF.

Importantly, the innovation of this study lies in highlighting packaging as a critical determinant of honey powder stability, moving beyond the production-focused approaches of previous research. By demonstrating that MAF pouches provide both superior preservation and enhanced portability, the study offers a practical solution that strengthens the commercial potential and consumer convenience of kelulut honey powders.

This study provides initial insights under controlled storage conditions, serving as a foundation for further investigations. Future research should extend to long-term stability assessments under varying environmental factors, explore a wider range of packaging materials, and incorporate anti-caking strategies to further enhance the functional quality and usability of honey powder products.

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Conflict of Interest

The authors declare no potential conflict of interests.

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