



## Research article

# Impact of raw and Dehumidified Stingless Bee (*Trigona* spp.) (*Trigona* spp.) honey on the physicochemical and stability of honey-milk beverages during storage

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## Abstract

**Importance of the work:** Formulating milk-honey beverages with acceptable colloidal stability is challenging, as Kelulut honey promotes pH-induced casein aggregation, leading to phase separation.

**Objectives:** To evaluate the effects of raw and dehumidified Kelulut honey on the physicochemical and colloidal behavior of milk during storage, as indicated by pH change, particle size and distribution, electrostatic interactions, rheological properties and phase separation.

**Materials and Methods:** Raw and dehumidified Kelulut honey (5–7% volume per volume) were incorporated into ultra-high temperature and pasteurized milk with varying fat contents. System behavior was assessed using the centrifugal sedimentation rate, separation index, particle size distribution (PSD), polydispersity index (PDI), zeta potential ( $\zeta$ ), apparent viscosity and pH during storage at 25°C and 4°C.

**Results:** Honey concentration and type influenced the initial physicochemical properties. At 5–6%, both honey types produced relatively uniform dispersions (PSD 257.0–265.2 nm; PDI 0.17–0.21), whereas 7% resulted in significantly larger particles (PSD 270.0–277.9 nm;  $p < 0.05$ ). Dehumidified honey had improved performance compared to raw honey, with a smaller particle size (266.8 nm versus 392.6 nm, respectively) and more a negative zeta potential (−28.00 mV versus −23.63 mV, respectively) during storage at 25°C. Milk type further affected system behavior, with pasteurized low-fat milk having the highest mean  $\pm$  SD phase separation ( $70 \pm 1.0\%$ ). The combination of 6% dehumidified honey and pasteurized full-cream milk yielded the most favorable physicochemical characteristics among the tested systems (particle size, 289.0 nm;  $\zeta$  −25.03 mV, after 14 d at 4°C).

**Main finding:** This most favorable formulation had improved resistance to destabilization and maintained acceptable dispersion within 72 hr and up to 14 d at 4°C, supporting its potential as a clean-label component for ready-to-serve milk-honey beverages intended for immediate or short-term consumption.

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## Introduction

Milk-based beverages have been consumed widely due to their balanced nutritional profile, providing high-quality proteins, calcium and essential vitamins (Fox et al., 2015). In more recent years, growing consumer demand for functional, minimally processed and clean-label products has stimulated interest in naturally sweetened dairy beverages (Granato et al., 2020). Honey is being explored increasingly as an alternative sweetener due to its antimicrobial, antioxidant and bioactive properties, which are primarily attributed to its organic acids, phenolic compounds, enzymes and sugars (Krushna, et al., 2007; da Silva et al., 2016). However, incorporating honey into liquid milk systems presents formulation challenges related to physicochemical and storage stability.

In parallel with the growing demand for clean-label dairy beverages, there has been a rapid expansion in the sale of milk tea and naturally sweetened milk-based drinks in both artisanal and commercial markets. Increasingly, consumers are seeking beverages with natural ingredients and functional benefits, driving growth in the functional and ready-to-drink dairy beverage sector (Cognitive Market Research, 2023; Gupta et al., 2023). Milk tea formulations are studied for their complex protein-polyphenol interactions and are gaining popularity across global markets (Wijegunawardhana et al., 2024). Commonly, these beverages use commercially processed milk, particularly ultra-high temperature (UHT) milk, because of its extended shelf life, microbiological safety, and suitability for large-scale beverage production (Chavan et al., 2011; de Souza et al., 2024). Natural sweeteners are being explored increasingly as alternatives to refined sugar, reflecting consumer preferences for natural and clean-label ingredients (Mahato et al., 2020). Among these, honey has gained particular attention in milk-based beverage formulations due to its natural origin and functional properties (Hussain and Narazi, 2024). However, the physicochemical compatibility of honey with heat-treated fluid milk systems remains insufficiently understood, particularly in relation to storage stability and phase behavior. At the same time, shifts in dietary behavior, including a growing reliance on sugar-sweetened beverages, have been consistently associated with increased obesity risk (Jannah et al., 2025), highlighting the need for reformulated dairy products with improved nutritional quality while maintaining consumer acceptability.

Honey is inherently acidic (pH 3.2–4.5) and contains organic acids, predominantly gluconic acid, which can lower the pH of milk systems (Samarghandian et al., 2017). In non-

fermented milk, a reduction in pH toward the isoelectric point of casein (pH 4.6) weakens electrostatic repulsion between casein micelles, promoting protein-protein interactions, micellar aggregation and phase separation (Walstra et al., 2005; Lucey, 2016). Such aggregation manifests as increased particle size, sedimentation and serum separation, compromising the physical stability and consumer acceptability of milk-honey beverages. Therefore, the types of stability referred to in the present study are physicochemical and colloidal stability, encompassing pH change, particle growth and distribution, electrostatic repulsion, rheological behavior and phase separation during storage.

Kelulut honey, also known as stingless bee (*Trigona* spp.) honey, differs markedly from conventional honey due to its higher moisture content (21–32%), lower pH and higher concentrations of organic acids and polyphenols (Chan et al., 2017; Shamsudin et al., 2019). The elevated water activity and acidity may exacerbate destabilization phenomena in milk systems where these characteristics enhance the nutritional and functional value. Additionally, raw Kelulut honey contains higher levels of organic acids and has elevated water activity, which may contribute to progressive acidification during storage, thereby influencing protein interactions and aggregation kinetics (Julika et al., 2020).

Other studies have examined primarily the incorporation of Kelulut honey in fermented dairy products, such as yoghurt, where controlled acidification is desirable. For example, Anwar et al. (2025) reported improved yoghurt texture at a low honey concentration (2–4%), whereas higher levels induced syneresis. However, these findings cannot be directly extrapolated to non-fermented milk systems, such as UHT and pasteurized milk, where protein stability depends on preserving the colloidal stability of casein micelles and preventing protein aggregation during storage and processing (Anema, 2019; de Souza et al., 2024). To date, the effects remain poorly understood of Kelulut honey addition on the physicochemical stability of fluid milk systems.

Dehumidification has been proposed as a processing strategy to improve honey suitability for beverage applications by reducing moisture content and water activity (Yap et al., 2019; Ikhsan et al., 2022). In addition, moderate-temperature dehumidification may influence the distribution and effective concentration of organic acids, potentially moderating pH reduction when honey is added to milk. By reducing excessive dilution and limiting rapid acidification, dehumidified honey may better preserve casein micelle integrity and improve colloidal stability (Hussain and Narazi, 2024). However, the extent remains unclear to which dehumidification alters honey–milk interactions across different milk matrices.

No study has undertaken a systematic investigation of the combined effects of honey type (raw versus dehumidified), honey concentration, milk fat content and milk heat treatment on the stability of non-fermented milk–honey systems. Therefore, the present study aimed to evaluate the effects of raw and dehumidified Kelulut honey on the colloidal and physical stability of commercial UHT and pasteurized milk with different fat contents during storage. Understanding these interactions is essential for the development of stable, clean-label milk–honey beverages with improved consumer acceptance.

## Materials and Methods

### Raw Materials

Full-cream and low-fat UHT milk, as well as full-cream and low-fat pasteurized milk, were obtained from a commercial dairy manufacturer and purchased from a retail supermarket in Serdang, Selangor, Malaysia. All milk products were transported to the laboratory under insulated conditions and stored according to the manufacturer's instructions prior to use. The UHT milk was stored at ambient temperature ( $25 \pm 2^\circ\text{C}$ ) before opening and refrigerated at  $4 \pm 1^\circ\text{C}$  after opening. The pasteurized milk was stored under refrigeration ( $4 \pm 1^\circ\text{C}$ ) throughout the study. All milk samples were used within their declared shelf-life and within 48 hr of opening.

Kelulut honey (*Heterotrigona itama*) was supplied by Kelulut Mak Lang Kelubee, Jasin, Melaka, Malaysia. Upon receipt, the raw honey was stored in sealed, food-grade containers at ambient temperature ( $25 \pm 2^\circ\text{C}$ ) in the absence of direct light. Dehumidified Kelulut honey was prepared using a food-grade dehumidifier (MINISESBEE; NizamPower Sdn Bhd; Johor, Malaysia) to reduce the moisture content to below 22%, in accordance with the Malaysian Standard MS 2683:2017 for Kelulut Honey (Malaysian Standard, 2017). Both the raw and dehumidified honey samples were stored under identical conditions.

Composition of the milk samples was obtained from product label declarations (Table 1). Differences in the fat and protein contents between the milk types were considered to evaluate the influence of compositional factors on honey-milk colloidal stability, as these parameters are known to affect protein interactions and emulsion behavior (Dickinson, 2001; Dalgleish, 2006).

Commercial UHT milk was selected as a standardized model system representing shelf-stable milk commonly used in ready-to-drink milk beverages and milk tea formulations. Its uniform composition and microbiological stability enable controlled evaluation of honey-induced physicochemical changes without any confounding effects of microbial activity. Pasteurized milk was included to represent fresh milk systems used in beverage preparation and product development contexts.

The mean  $\pm$  SD values for the pH and moisture content of the raw Kelulut honey were  $3.4 \pm 0.1$  and  $33.1 \pm 0.05\%$ , respectively, whereas for the dehumidified honey, they were  $3.5 \pm 0.1$  and  $21.2 \pm 0.36\%$ , respectively. All experiments were conducted using a single batch of honey to minimize any compositional variability.

### Preliminary study

Preliminary screening was conducted by adding 2–15% (volume per volume, v/v) raw Kelulut honey to UHT full-cream milk. Visible phase separation was observed at concentrations above 7% after 24 hr storage at  $25 \pm 2^\circ\text{C}$ . Based on these observations, honey concentrations of 5% (v/v), 6% (v/v) and 7% (v/v) were selected for subsequent experiments to represent the upper formulation range commonly applied in sweetened milk beverages, while capturing the transition region of colloidal instability. This concentration range provided a moderate sweetness contribution from honey without excessive dilution of the milk matrix.

### Sample preparation

For each treatment, a 10 mL aliquot was transferred into

**Table 1** Composition (mean  $\pm$  SD) of milk samples used

| Sample                                 | Fat (%)       | Protein (%)   | Source        |
|----------------------------------------|---------------|---------------|---------------|
| Full-cream ultra-high temperature milk | $3.8 \pm 0.1$ | $3.4 \pm 0.1$ | Product label |
| Low-fat ultra-high temperature milk    | $1.5 \pm 0.1$ | $3.2 \pm 0.1$ | Product label |
| Full-cream pasteurized milk            | $3.8 \pm 0.1$ | $3.4 \pm 0.1$ | Product label |
| Low-fat pasteurized milk               | $1.5 \pm 0.1$ | $3.4 \pm 0.1$ | Product label |

a sterile 15 mL polypropylene tube and shaken manually for 10 s to achieve dispersion, based on a modified duration from Sun et al., (2017). Manual shaking was selected as a simple and application-relevant dispersion method (Pradhan et al., 2016) and to simulate commercial milk-tea based beverages preparation conditions (available at cafes in Malaysia), where typically, viscous sweeteners are incorporated without controlled shear or standardized mixing intensity. In addition, this approach minimized the application of high shear that could disrupt shear-sensitive casein aggregates and alter the native colloidal structure (Fox and McSweeney, 2003; Mediawaththe et al., 2024).

Due to the high viscosity of the dehumidified honey, dispersion was evaluated based on macroscopic uniformity (Hu et al., 2017), with no visible phase separation observed after mixing. Samples were inverted gently prior to analysis to maintain consistency (Fahmi et al., 2026).

All treatments were prepared in triplicate and analyzed immediately or stored at 25°C or 4°C, as described in Section 2.4.

### Storage study

The honey-milk samples were stored under specified temperature and time conditions to simulate market and household environments. Samples were stored at ambient temperature (25 ± 2°C) for 48 hr, with sampling at 0 hr, 6 hr, 12 hr, 24 hr, 36 hr and 48 hr and under refrigerated conditions (4 ± 1°C) for 14 d, with sampling at 0 d, 3 d, 5 d, 7 d, 10 d and 14 d. Samples were stored in sealed tubes under static conditions and remained undisturbed throughout the study period. These storage conditions were adapted from Pereda et al (2007) and Shao et al., (2023) who studied physicochemical stability in dairy beverage systems.

### Physicochemical analysis

#### Centrifugal sedimentation rate

The centrifugal sedimentation rate (CSR) was determined following Fan et al. (2024b), with a minor modification in the sample volume. The sedimented fraction was collected and weighed and CSR percentage was calculated using Equation 1:

$$\text{CSR} = (m_2 - m_1) / m_0 \times 100 \quad (1)$$

where  $m_0$  is the sample mass,  $m_1$  is the mass of the centrifuge tube, and  $m_2$  is the mass of the centrifuge tube after discarding

the supernatant, with all measurements in milligrams.

#### Separation index

The separation index (SI) was assessed to determine samples storage stability and calculated using Equation 2 (Ren et al., 2023):

$$\text{SI} (\%) = (1 - H_u/H_t) \times 100 \quad (2)$$

where  $H_t$  is the total sample height and  $H_u$  is the upper phase height.

SI was monitored during 72 hr (25°C) and 336 hr (4°C).

#### Particle size distribution and polydispersity index

The particle size distribution (PSD) and polydispersity index (PDI) were measured using a Zetasizer Nano-ZS (Malvern Instruments Ltd.; UK). Samples were diluted at 1:100 (v/v) with distilled water before analysis at 25°C using dynamic light scattering (Mootse et al., 2014). The refractive index of the real part was 1.76. The refractive index of the medium was 1.33 (Fan et al., 2024a).

#### Zeta potential

The zeta potential ( $\zeta$ ) was determined using a Zetasizer Nano ZS (Malvern Instruments Ltd.; UK based on electrophoretic light scattering (Ménard et al., 2010). Samples were diluted (1:100, v/v) with distilled water prior to measurement to minimize multiple scattering effects and ensure reliable  $\zeta$ -potential determination. Although dilution may alter the absolute  $\zeta$ -values compared to the undiluted system, the measurements reliably reflected relative differences between treatments. This analysis has been used widely to compare colloidal stability trends in dairy systems (McClements, 2004; Sejersen et al., 2007). Sample were measured at 25 ± 1°C after 2 min equilibration. Each sample was analyzed in triplicate.

#### Rheological measurements

The rheological properties were measured using a rotational rheometer (HAAKE Mars 40; Thermo Scientific; USA) with 60 mm parallel plates at 25°C and a 300 µm gap. The shear rate was increased in the range 0–100/s to determine apparent viscosity (Singh et al., 2019; Kot et al., 2023).

#### pH measurement

The pH was measured using a calibrated digital pH meter (SmartSensor pH828+; Tektronix; China). The pH values were registered after calibration of the pH meter readings using three buffer solutions (pH 4.0, pH 6.86, pH 9.18), according to

Aboulghazzi and Lyoussi (2022). Each measurement was taken in triplicate at 25°C.

### Apparent viscosity

The apparent viscosity was measured using a rotational rheometer (RheolabQC; Anton Paar GmbH; Austria) combining the methods of Trávníček et al (2012) and Ince et al (2025). Measurements were conducted with the use of cone-and-plate measuring geometry. The diameter of the cone was 50 mm at an angle of 1°, a shear rate of 60/s and a temperature of 25°C. The measurement of shear stress dependence on shear rate was performed in the range of 0–100/s.

### Statistical analysis

Data were analyzed using Minitab® version 22 (Minitab LLC; USA). One-way analysis of variance (ANOVA) and Tukey's honest significant difference test ( $p < 0.05$ ) were applied to compare treatment effects. For time-dependent studies, a general linear model (GLM) ANOVA was used to evaluate the effects of storage time, honey type and the interaction between honey concentration and milk type. The results were presented as mean  $\pm$  SD values. All experiments were conducted in triplicate and repeated in two independent experimental runs to ensure reproducibility.

## Results and Discussion

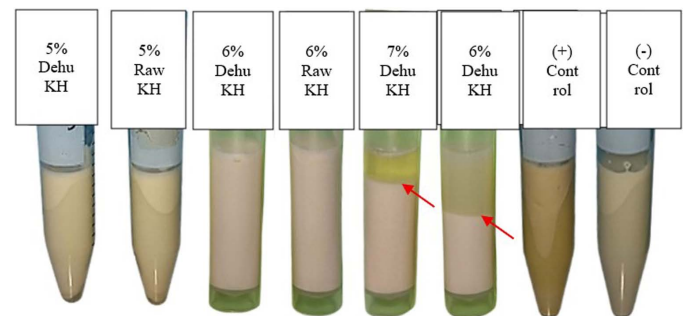
### Determination of optimal concentration and type of Kelulut honey for stability study of ultra-high temperature milk mixtures

This section examines the influence of Kelulut honey

concentration (5–7%, v/v) and honey type (raw and dehumidified) on the physicochemical stability of UHT full-cream milk. Stability was evaluated using the CSR, separation index, PSD, PDI, ( $\zeta$ -potential) and apparent viscosity.

### Centrifugal sedimentation rate

As shown in Table 2 and Fig. 1, the UHT milk with 5–6% Kelulut honey maintained a CSR of 0%, comparable to the controls ( $p > 0.05$ ). At 7%, sedimentation increased significantly, with the raw honey causing greater destabilization (59%) than the dehumidified honey (27%). Based on these results, the Kelulut honey could be incorporated up to 6% (v/v) without compromising centrifugal stability, whereas higher concentrations promoted aggregation and sediment formation. The increased sedimentation at elevated honey levels could be attributed to acidification-driven destabilization of casein micelles; Kelulut honey contains organic acids, predominantly gluconic acid, which lower the system pH and increase ionic strength (Samarghandian et al., 2017).



**Fig. 1** Visual appearance of milk samples after centrifugation at 4,192.5×g for 10 min, where red arrows indicate phase separation in samples containing 7% Kelulut honey (KH), whereas control samples and formulations with lower honey concentrations remain visually stable and Dehu = dehumidified

**Table 2** Centrifugal sedimentation rate, particle size distribution, polydispersity index, zeta potential of milk-honey samples

| Treatment                  | Concentration | Centrifugal sedimentation rate (%) | Particle size distribution (d.nm) | Polydispersity index (PDI)    | Zeta potential (mV)             |
|----------------------------|---------------|------------------------------------|-----------------------------------|-------------------------------|---------------------------------|
| Raw Kelulut honey          | 5%            | 0 $\pm$ 0.00 <sup>c</sup>          | 262.6 $\pm$ 1.48 <sup>def</sup>   | 0.21 $\pm$ 0.01 <sup>b</sup>  | -31.13 $\pm$ 0.29 <sup>c</sup>  |
|                            | 6%            | 0 $\pm$ 0.00 <sup>c</sup>          | 265.2 $\pm$ 2.28 <sup>cde</sup>   | 0.17 $\pm$ 0.02 <sup>c</sup>  | -30.30 $\pm$ 0.60 <sup>bc</sup> |
|                            | 7%            | 59 $\pm$ 0.10 <sup>a</sup>         | 277.9 $\pm$ 3.15 <sup>b</sup>     | 0.22 $\pm$ 0.01 <sup>ab</sup> | -28.46 $\pm$ 0.41 <sup>a</sup>  |
| Dehumidified Kelulut honey | 5%            | 0 $\pm$ 0.00 <sup>c</sup>          | 257.0 $\pm$ 2.39 <sup>f</sup>     | 0.19 $\pm$ 0.00 <sup>bc</sup> | -32.90 $\pm$ 0.30 <sup>d</sup>  |
|                            | 6%            | 0 $\pm$ 0.00 <sup>c</sup>          | 259.3 $\pm$ 0.60 <sup>ef</sup>    | 0.19 $\pm$ 0.01 <sup>bc</sup> | -31.13 $\pm$ 0.30 <sup>c</sup>  |
|                            | 7%            | 27 $\pm$ 0.30 <sup>b</sup>         | 270.8 $\pm$ 1.78 <sup>c</sup>     | 0.19 $\pm$ 0.01 <sup>bc</sup> | -28.76 $\pm$ 0.55 <sup>ab</sup> |
| Positive (+) control       |               | 0 $\pm$ 0.00 <sup>c</sup>          | 297.7 $\pm$ 3.31 <sup>a</sup>     | 0.25 $\pm$ 0.00 <sup>a</sup>  | -35.83 $\pm$ 1.33 <sup>c</sup>  |
| Negative (-) control       |               | 0 $\pm$ 0.00 <sup>c</sup>          | 268.4 $\pm$ 0.34 <sup>cd</sup>    | 0.20 $\pm$ 0.01 <sup>bc</sup> | -36.50 $\pm$ 0.37 <sup>c</sup>  |

Negative (-) control = ultra-high temperature milk only; Positive (+) control = ultra-high temperature milk with 10% caramel syrup.

<sup>a-f</sup> = values (mean  $\pm$  SD,  $n = 3$ ) with different lowercase superscript letters within column are significantly ( $p < 0.05$ ) different.

These changes reduced electrostatic repulsion and partially screened surface charges on the casein micelles, promoting protein aggregation and the formation of dense sediment under centrifugal stress. (Arii and Nishizawa, 2020; da Silva et al., 2024). Similar acid-induced aggregation phenomena have been reported in acidified and honey-supplemented dairy systems, where progressive reduction in colloidal stability resulted in sedimentation and phase separation (Arii and Nishizawa, 2020). The lower CSR values in the dehumidified honey formulations may have been associated with reduced levels of moisture content and water activity, which moderate protein hydration and ionic interactions, delaying aggregation under centrifugal stress (Sramek et al., 2017; Ikhsan et al., 2022).

#### Particle size distribution and polydispersity index

The honey concentration and type significantly influenced the particle size and PDI (Table 2). The dehumidified honey at 5–6% had the smallest particles (diameter 257.0–259.3 nm), while 7% increased the particle size, with the raw honey having larger particles than all dehumidified honey samples. Increasing the honey concentration promotes acid-induced destabilization of the casein micelles by reducing the surface charge and weakening calcium phosphate crosslinks, allowing attractive forces to dominate and drive clustering (Lucey, 2016). The larger particles observed in the raw Kelulut honey indicated stronger aggregation, likely due to the higher organic acid content and water activity that enhanced protein mobility and collision frequency (Dalgleish and Corredig, 2012). Similar aggregation behavior occurs in acidified milk near the isoelectric region of casein (Lucey, 2016).

The PDI values supported these trends. The 6% raw Kelulut honey sample had the lowest PDI ( $0.17 \pm 0.02$ ), producing the most uniform particle size distribution, whereas increasing the raw honey concentration to 7% significantly increased heterogeneity ( $PDI = 0.22 \pm 0.01$ ). In contrast, the dehumidified honey maintained its PDI value (0.19), suggesting more regulated colloidal interactions, likely associated with reduced water activity (Chen et al., 2021). This aligned with reports of stingless bee honey-based nanoemulsions, where system stability was associated with a narrow particle size distribution and structural uniformity (Rozman et al., 2021).

#### Zeta potential

The zeta potential was significantly affected by the honey type and concentration. The highest magnitude of negative zeta potential was observed at 5% dehumidified honey ( $-32.90$  mV), indicating stronger electrostatic repulsion, whereas 7% addition

reduced electrostatic stabilization, particularly in raw honey formulations ( $-28.46$  mV), indicating weakened electrostatic repulsion, while 6% raw honey remained near the stability threshold. This concentration-dependent reduction in  $\zeta$ -potential was likely associated with increased ionic strength and acidity, which partially screened surface charges on the casein micelles and reduced interparticle repulsion (Lucey, 2016). In contrast, the dehumidified honey systems maintained more negative  $\zeta$ -values, suggesting better preservation of electrostatic stabilization, potentially due to reduced water activity and moderated physicochemical interactions. A similar relationship between more negative  $\zeta$ -potential and improved stability has been reported in acidified milk systems (Sejersen et al., 2007), where stabilizer addition increased the negative surface charge and enhanced dispersion stability, while processing-induced changes that reduced the  $\zeta$ -potential resulted in weakened colloidal stability.

#### Rheological properties

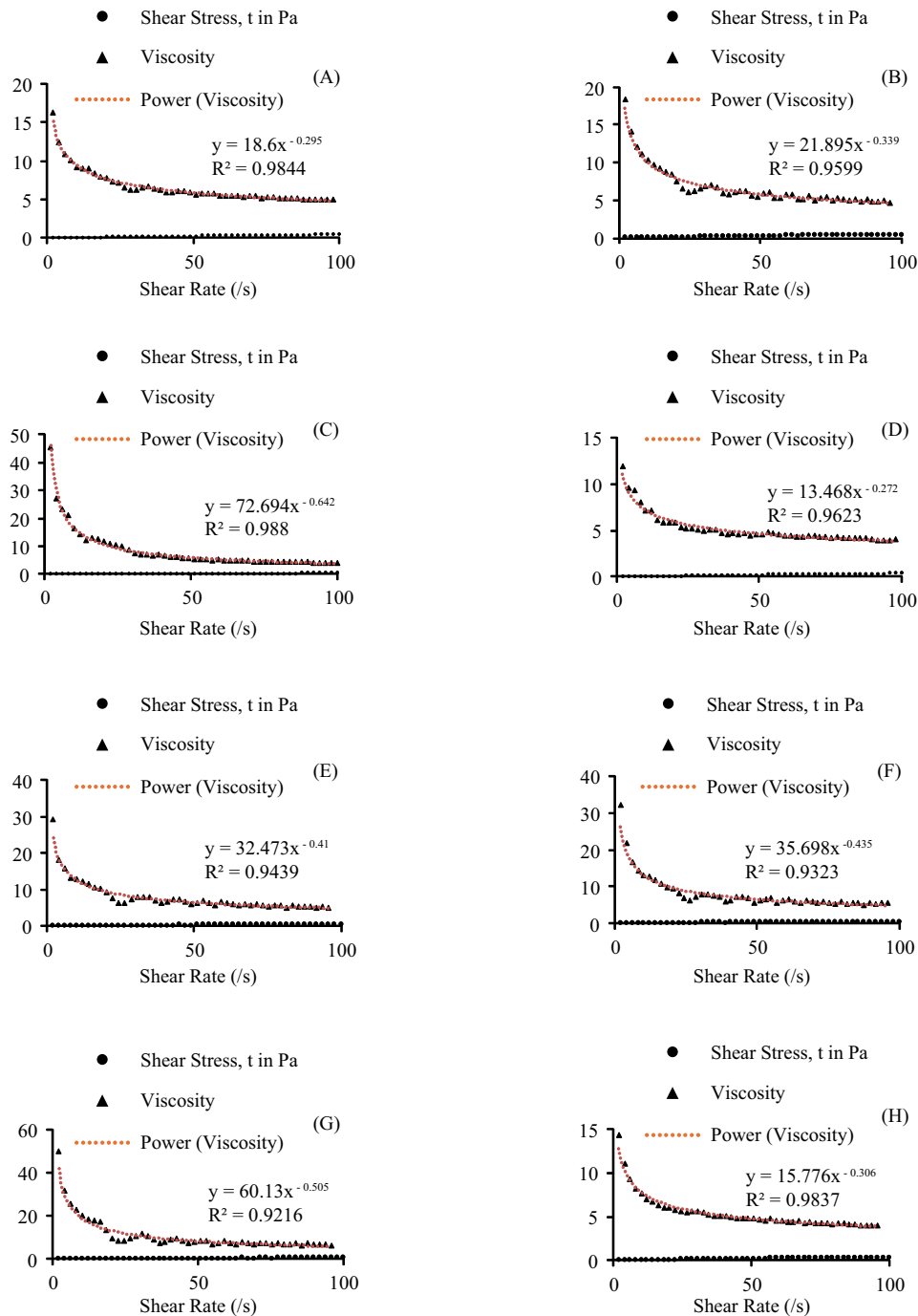
All the tested milk-honey mixtures exhibited pseudoplastic (shear-thinning) behavior, whereas both the raw and dehumidified Kelulut honey showed Newtonian flow, indicating that non-Newtonian behavior originated from modifications of the milk colloidal structure rather than from the honey rheology, as reflected in the flow curves (Fig. 2). Apparent viscosity at 50/s ( $\eta_{50}$ ) differed significantly among formulations (Table 3).

The highest viscosity was at 6% raw honey ( $7.76 \pm 0.12$  mPa·s), consistent with reductions in the pH and ionic strength of electrostatic repulsion between the casein micelles (Fox and McSweeney, 2013). Partial aggregation and the formation of weak, shear-sensitive flocculated structures increased resistance to flow at low shear without forming a continuous gel network, explaining the observed pseudoplastic behavior network (Pushpadass et al., 2019). This viscosity increase reflected microstructural restructuring of the casein system

**Table 3** Calculated apparent viscosity at shear rate of 50/s ( $\eta_{50}$ ) for milk-honey samples and controls

| Sample                               | $\eta_{50}$ (mPa·s)  |
|--------------------------------------|----------------------|
| 5% Raw honey                         | $5.87 \pm 0.13^b$    |
| 5% Dehumidified honey                | $5.15 \pm 0.07^{cd}$ |
| 6% Raw honey                         | $7.76 \pm 0.12^a$    |
| 6% Dehumidified honey                | $4.36 \pm 0.07^e$    |
| 7% Raw honey                         | $5.27 \pm 0.10^c$    |
| 7% Dehumidified honey                | $5.20 \pm 0.07^{cd}$ |
| Positive control (10% caramel syrup) | $5.36 \pm 0.06^c$    |
| Negative control (milk only)         | $4.96 \pm 0.05^d$    |

<sup>a-e</sup> = values (mean  $\pm$  SD,  $n = 3$ ) with different lowercase superscript letters within column are significantly ( $p < 0.05$ ) different.



**Fig. 2** Flow curves of milk enriched with Kelulut honey at different concentrations: (A) 5% raw honey, (B) 5% dehumidified honey, (C) 6% raw honey, (D) 6% dehumidified honey, (E) 7% raw honey, (F) 7% dehumidified honey, (G) positive control (milk with caramel syrup), and (H) negative control (milk without honey). R<sup>2</sup> = coefficient of determination.

rather than thickening by honey constituents.

At 7% honey, the viscosity did not increase further and approached the control values, suggesting excessive aggregation and reduced microstructural uniformity (Albay

et al., 2025), consistent with the PSD and PDI results. In contrast, 6% dehumidified honey had a lower viscosity ( $4.36 \pm 0.07$  mPa·s), indicating moderated protein interactions, likely due to the reduced moisture content and altered acid

distribution after dehumidification (Ikhsan et al., 2022).

Similar viscosity trends dominated by protein aggregation rather than sugar networking have been reported in honey-fortified and acidified dairy systems. Honey polysaccharides are present at low levels and are therefore unlikely to contribute to independent network formation, with rheological behavior instead being dominated by pH-mediated protein-protein interactions (Pushpadass et al., 2019).

Based on the combined stability, rheological and physicochemical assessments (Sections 3.1.1–3.1.4), the 6% Kelulut honey formulation was identified as optimal and selected for subsequent storage stability studies.

### *Effect of Kelulut honey on stability of different milk types during storage*

The milk-Kelulut honey systems, differing in fat content and thermal processing, were evaluated at 25°C using pH, sedimentation behavior, particle characteristics, zeta potential and viscosity (Table 4). Honey addition reduced the initial pH of all systems, followed by progressive acidification during storage.

This effect was most pronounced in the UHT low-fat milk with raw honey (from pH 5.6 to 4.4 at 72 hr), whereas systems containing dehumidified honey and full-cream milk had relatively slower pH declines. These pH changes were closely associated with physicochemical stability: although all samples initially resisted centrifugal stress (CSR = 0%), phase separation increased over time, with raw honey promoting earlier and more extensive separation, particularly in the low-fat and pasteurized milk systems.

Primarily, the observed destabilization was attributed to pH-driven reduction in electrostatic repulsion as the system approached the casein isoelectric region (pH 4.6–4.8), promoting casein aggregation and serum release (Lucey, 2016; Popescu, 2019). A lower fat content further reduced steric stabilization, increasing susceptibility to phase separation (Singh, 2006; Dalglish and Corredig, 2012). Consistent with this behavior, the particle size increased progressively in all systems during storage, indicating aggregation-driven structural evolution. While no significant differences were observed at 0 h, by 48 h, the raw honey formulations exhibited significantly larger particles than dehumidified honey systems and controls, particularly in low-fat and pasteurized milk.

Generally, the PDI values remained below 0.30, indicating relatively homogeneous dispersions, although transient increases in the raw honey systems during early storage suggested localized and uneven aggregation (Danaei et al., 2018). As

**Table 4** Physicochemical parameters (pH, stability index (SI), zeta potential (ZP), particle size distribution (PSD), polydispersity index (PDI) and apparent viscosity (AV)) of milk-Kelulut honey systems during storage at 25°C

| Parameter              | Storage time (hr)      | pH                    | SI (%)               |                      |                       | ZP (mV)               |                          |                           | PSD (nm)                  |                         |                          | PDI                     |                        |                         | AV                      |                        |                         |                         |
|------------------------|------------------------|-----------------------|----------------------|----------------------|-----------------------|-----------------------|--------------------------|---------------------------|---------------------------|-------------------------|--------------------------|-------------------------|------------------------|-------------------------|-------------------------|------------------------|-------------------------|-------------------------|
|                        | 0                      | 24                    | 72                   | 6                    | 24                    | 48                    | 0                        | 24                        | 48                        | 0                       | 24                       | 48                      | 0                      | 24                      | 48                      | 0                      | 24                      | 48                      |
| Milk type              |                        |                       |                      |                      |                       |                       |                          |                           |                           |                         |                          |                         |                        |                         |                         |                        |                         |                         |
| UHT full cream         | 6 % Raw honey          | 5.4±0.0 <sup>a</sup>  | 5.2±0.0 <sup>a</sup> | 5.0±0.2 <sup>f</sup> | 31.0±1.7 <sup>b</sup> | 49.6±1.5 <sup>d</sup> | -27.26±0.38 <sup>c</sup> | -24.26±0.15 <sup>ab</sup> | 23.63±0.15 <sup>a</sup>   | 217.6±2.5 <sup>d</sup>  | 345.0±5.0 <sup>b</sup>   | 392.6±4.7 <sup>c</sup>  | 0.51±0.7 <sup>a</sup>  | 0.31±0.3 <sup>bc</sup>  | 0.29±0.01 <sup>c</sup>  | 6.03±0.5 <sup>c</sup>  | 7.30±0.00 <sup>b</sup>  | 9.70±0.00 <sup>b</sup>  |
|                        | 6 % Dehumidified honey | 5.4±0.0 <sup>a</sup>  | 5.2±0.0 <sup>a</sup> | 5.0±0.2 <sup>f</sup> | -                     | 25±1.0 <sup>a</sup>   | -37.9±1.83 <sup>c</sup>  | -28.56±0.05 <sup>a</sup>  | -28.00±0.10 <sup>a</sup>  | 239.0±1.6 <sup>d</sup>  | 260.3±5.6 <sup>ab</sup>  | 266.8±3.5 <sup>a</sup>  | 0.23±0.2 <sup>c</sup>  | 0.29±0.3 <sup>a</sup>   | 0.31±0.09 <sup>a</sup>  | 6.03±0.5 <sup>c</sup>  | 9.70±0.00 <sup>b</sup>  | 9.80±0.00 <sup>b</sup>  |
|                        | (+) Control            | 5.8±0.0 <sup>a</sup>  | 5.7±0.0 <sup>a</sup> | 5.5±0.2 <sup>f</sup> | -                     | 50±0.1 <sup>a</sup>   | -35.23±0.60 <sup>b</sup> | -33.90±0.62 <sup>ab</sup> | -33.43±0.57 <sup>a</sup>  | 237.6±2.7 <sup>a</sup>  | 243.0±2.8 <sup>a</sup>   | 244.8±2.8 <sup>a</sup>  | 0.26±0.0 <sup>a</sup>  | 0.28±0.0 <sup>a</sup>   | 0.29±0.04 <sup>a</sup>  | 6.90±0.1 <sup>d</sup>  | 11.80±0.00 <sup>a</sup> | 13.80±0.00 <sup>b</sup> |
|                        | (-) Control            | 5.9±0.1 <sup>a</sup>  | 5.8±0.0 <sup>a</sup> | 5.6±0.3 <sup>e</sup> | -                     | 0.0±0.0               | -35.96±0.83 <sup>a</sup> | -35.46±0.76 <sup>a</sup>  | -35.16±0.76 <sup>a</sup>  | 234.8±2.2 <sup>a</sup>  | 242.0±2.6 <sup>a</sup>   | 244.6±2.5 <sup>a</sup>  | 0.23±0.1 <sup>c</sup>  | 0.27±0.1 <sup>ab</sup>  | 0.28±0.01 <sup>a</sup>  | 6.03±0.5 <sup>c</sup>  | 10.50±0.00 <sup>b</sup> | 10.90±0.00 <sup>b</sup> |
| UHT low fat            | 6 % Raw honey          | 5.6±0.0 <sup>a</sup>  | 5.1±0.1 <sup>a</sup> | 4.4±0.3 <sup>a</sup> | -                     | 50.0±1.0 <sup>a</sup> | -33.60±0.20 <sup>d</sup> | -24.60±0.55 <sup>a</sup>  | -24.20±0.45 <sup>a</sup>  | 275.8±3.0 <sup>d</sup>  | 296.0±4.1 <sup>b</sup>   | 319.7±2.2 <sup>a</sup>  | 0.21±0.0 <sup>a</sup>  | 0.21±0.0 <sup>a</sup>   | 0.24±0.01 <sup>a</sup>  | 5.20±0.0 <sup>d</sup>  | 6.60±0.00 <sup>b</sup>  | 10.00±0.00 <sup>a</sup> |
|                        | 6 % Dehumidified honey | 5.6±0.0 <sup>a</sup>  | 5.2±0.0 <sup>a</sup> | 4.6±0.2 <sup>b</sup> | -                     | 35.0±1.0 <sup>a</sup> | -27.00±0.17 <sup>d</sup> | -24.36±0.40 <sup>ab</sup> | -23.56±0.72 <sup>a</sup>  | 277.6±1.4 <sup>b</sup>  | 290.3±5.0 <sup>ab</sup>  | 302.1±2.2 <sup>a</sup>  | 0.23±0.0 <sup>a</sup>  | 0.19±0.1 <sup>bc</sup>  | 0.21±0.01 <sup>ab</sup> | 5.50±0.0 <sup>d</sup>  | 6.30±0.07 <sup>a</sup>  | 6.50±0.00 <sup>a</sup>  |
|                        | (+) Control            | 6.0±0.0 <sup>a</sup>  | 5.7±0.0 <sup>a</sup> | 5.2±0.1 <sup>a</sup> | -                     | 20.0±1.0 <sup>a</sup> | -34.30±0.79 <sup>c</sup> | -30.30±0.30 <sup>b</sup>  | -26.30±0.30 <sup>b</sup>  | 305.0±10.0 <sup>b</sup> | 323.3±12.0 <sup>ab</sup> | 344.6±16.1 <sup>a</sup> | 0.32±0.3 <sup>a</sup>  | 0.27±0.1 <sup>ab</sup>  | 0.28±0.01 <sup>ab</sup> | 6.50±0.1 <sup>c</sup>  | 6.67±0.57 <sup>b</sup>  | 10.40±0.00 <sup>a</sup> |
|                        | (-) Control            | 6.1±0.0 <sup>a</sup>  | 5.8±0.0 <sup>a</sup> | 5.3±0.2 <sup>a</sup> | -                     | 0.0±0.0               | -31.86±0.15 <sup>d</sup> | -30.40±0.10 <sup>b</sup>  | -29.76±0.20 <sup>a</sup>  | 289.9±3.1 <sup>a</sup>  | 295.5±0.5 <sup>ab</sup>  | 296.6±3.9 <sup>a</sup>  | 0.21±0.1 <sup>a</sup>  | 0.20±0.1 <sup>a</sup>   | 0.21±0.01 <sup>a</sup>  | 6.00±0.0 <sup>a</sup>  | 6.33±0.57 <sup>b</sup>  | 6.50±0.00 <sup>a</sup>  |
| Pasteurized full cream | 6 % Raw honey          | 5.4±0.00 <sup>a</sup> | 5.4±0.1 <sup>a</sup> | 5.2±0.1 <sup>a</sup> | -                     | 60.0±1.0 <sup>a</sup> | -31.60±0.72 <sup>d</sup> | -26.96±0.20 <sup>b</sup>  | -25.03±0.30 <sup>a</sup>  | 247.1±0.6 <sup>c</sup>  | 280.9±3.5 <sup>ab</sup>  | 284.7±5.5 <sup>a</sup>  | 0.24±0.0 <sup>ab</sup> | 0.24±0.0 <sup>ab</sup>  | 0.27±0.07 <sup>a</sup>  | 4.50±0.00 <sup>a</sup> | 5.76±0.57 <sup>a</sup>  | 16.10±0.00 <sup>a</sup> |
|                        | 6 % Dehumidified honey | 5.5±0.00 <sup>a</sup> | 5.4±0.6 <sup>a</sup> | 5.2±0.1 <sup>a</sup> | -                     | 35.0±1.0 <sup>a</sup> | -29.16±0.15 <sup>b</sup> | -28.80±0.72 <sup>a</sup>  | -26.20±0.79 <sup>a</sup>  | 246.7±3.1 <sup>d</sup>  | 272.7±4.2 <sup>a</sup>   | 278.2±2.5 <sup>a</sup>  | 0.23±0.0 <sup>a</sup>  | 0.24±0.1 <sup>ab</sup>  | 0.26±0.07 <sup>a</sup>  | 4.93±0.05 <sup>d</sup> | 11.80±0.00 <sup>b</sup> | 15.06±0.83 <sup>a</sup> |
|                        | (+) Control            | 6.0±0.1 <sup>a</sup>  | 5.9±0.1 <sup>a</sup> | 5.9±0.6 <sup>a</sup> | -                     | 10.0±1.0 <sup>a</sup> | -29.86±0.15 <sup>a</sup> | -29.13±0.56 <sup>ab</sup> | -28.96±0.15 <sup>ab</sup> | 276.8±1.9 <sup>c</sup>  | 284.1±0.7 <sup>ab</sup>  | 285.0±0.9 <sup>a</sup>  | 0.24±0.0 <sup>a</sup>  | 0.26±0.0 <sup>a</sup>   | 0.27±0.04 <sup>a</sup>  | 6.00±0.00 <sup>a</sup> | 11.76±0.25 <sup>b</sup> | 15.00±0.00 <sup>a</sup> |
|                        | (-) Control            | 6.0±0.1 <sup>a</sup>  | 6.0±0.1 <sup>a</sup> | 5.9±0.1 <sup>a</sup> | -                     | 25±1.0 <sup>a</sup>   | -31.86±0.15 <sup>d</sup> | -30.40±0.10 <sup>b</sup>  | -29.76±0.20 <sup>a</sup>  | 261.3±0.8 <sup>a</sup>  | 278.1±1.7 <sup>ab</sup>  | 282.8±1.8 <sup>a</sup>  | 0.19±0.1 <sup>a</sup>  | 0.23±0.00 <sup>ab</sup> | 0.24±0.05 <sup>a</sup>  | 5.10±0.00 <sup>a</sup> | 6.40±0.10 <sup>a</sup>  | 7.50±0.00 <sup>a</sup>  |
| Pasteurized low fat    | 6 % Raw honey          | 5.4±0.0 <sup>a</sup>  | 5.3±0.1 <sup>a</sup> | 5.0±0.1 <sup>a</sup> | -                     | 70±1.0 <sup>a</sup>   | -29.23±0.92 <sup>b</sup> | -24.93±0.20 <sup>a</sup>  | -23.63±0.20 <sup>a</sup>  | 204.8±1.3 <sup>c</sup>  | 251.2±1.0 <sup>b</sup>   | 256.8±1.4 <sup>a</sup>  | 0.21±0.1 <sup>b</sup>  | 0.22±0.0                | 0.25±0.10               | 4.20±0.00 <sup>a</sup> | 5.90±0.00 <sup>b</sup>  | 14.53±0.75 <sup>a</sup> |
|                        | 6 % Dehumidified honey | 5.5±0.0 <sup>a</sup>  | 5.3±0.6 <sup>a</sup> | 5.1±0.3 <sup>a</sup> | -                     | 20±1.0 <sup>a</sup>   | -31.46±0.68 <sup>b</sup> | -29.67±0.37 <sup>a</sup>  | -29.40±0.88 <sup>a</sup>  | 201.4±1.7 <sup>c</sup>  | 221.9±0.4 <sup>a</sup>   | 232.7±0.0 <sup>a</sup>  | 0.17±0.1 <sup>b</sup>  | 0.23±0.1 <sup>ab</sup>  | 0.22±0.17 <sup>a</sup>  | 4.40±0.00 <sup>a</sup> | 5.46±0.15 <sup>b</sup>  | 13.20±0.00 <sup>a</sup> |
|                        | (+) Control            | 6.0±0.0 <sup>a</sup>  | 5.9±0.8 <sup>a</sup> | 5.7±0.2 <sup>a</sup> | -                     | 35±1.0 <sup>a</sup>   | -31.36±0.51 <sup>c</sup> | -30.10±0.43 <sup>ab</sup> | -29.33±0.37 <sup>a</sup>  | 236.8±1.8 <sup>a</sup>  | 242.5±1.8 <sup>a</sup>   | 243.8±3.6 <sup>a</sup>  | 0.25±0.0 <sup>a</sup>  | 0.25±0.7 <sup>a</sup>   | 0.26±0.09 <sup>a</sup>  | 5.70±0.00 <sup>a</sup> | 13.00±0.00 <sup>a</sup> | 12.50±0.00 <sup>a</sup> |
|                        | (-) Control            | 6.0±0.0 <sup>a</sup>  | 5.9±0.8 <sup>a</sup> | 5.7±0.2 <sup>a</sup> | -                     | 63±1.0 <sup>a</sup>   | -33.13±0.32 <sup>a</sup> | -32.80±0.10 <sup>b</sup>  | -32.60±0.10 <sup>a</sup>  | 210.3±0.6 <sup>d</sup>  | 217.2±0.7 <sup>a</sup>   | 218.8±0.7 <sup>a</sup>  | 0.16±0.2 <sup>b</sup>  | 0.19±0.2 <sup>ab</sup>  | 0.20±0.02 <sup>a</sup>  | 5.10±0.00 <sup>a</sup> | 9.56±0.15 <sup>b</sup>  | 11.00±0.00 <sup>a</sup> |

UHT = ultra-high temperature. Negative (-) control = ultra-high temperature milk only; Positive (+) control = ultra-high temperature milk with 10% caramel syrup.

Values (mean ± SD,  $n = 3$ ) with different lowercase superscripts within same parameter are significantly ( $p < 0.05$ ) different among treatments and storage times, according to Tukey's honest significant difference test. Statistical comparisons performed independently for each parameter. (+) Control = positive control (milk + caramel syrup); (-) Control = negative control (milk only).

storage progressed, the PDI values converged, despite continued particle growth, indicating structural reorganization toward more uniform aggregates. In parallel, the zeta potential magnitude decreased in all systems, reflecting weakened electrostatic stabilization (McClements, 2004), with more pronounced reductions observed in the raw honey formulations. The dehumidified honey systems maintained comparatively more negative values, consistent with moderated aggregation behavior.

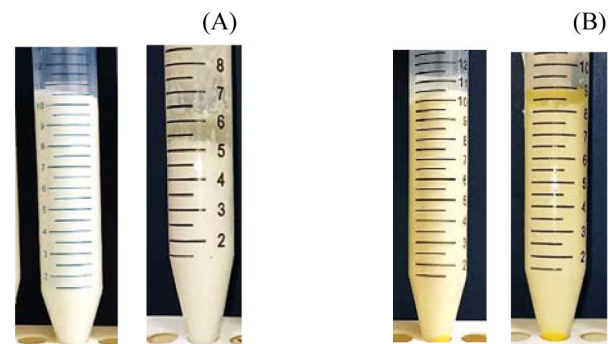
The apparent viscosity increased concurrently during storage, particularly in the low-fat systems, reflecting aggregation-induced structuring within the colloidal matrix (Lukey, 2016). Generally, the raw honey induced stronger viscosity increases than the dehumidified honey, consistent with the formers greater extent of acidification and aggregation. Overall, the combined trends in pH, sedimentation, particle size, zeta potential and viscosity indicated that storage behavior in milk-Kelulut honey systems was governed by acidification-driven casein aggregation, modulated by milk composition, heat treatment and honey type.

#### *Physicochemical changes of milk-Kelulut honey systems during chill storage*

The long-term physicochemical stability of the milk-Kelulut honey systems during chilled storage was evaluated using the formulation that had the highest stability under ambient conditions (Section 3.2). Pasteurized full-cream milk containing 6% dehumidified Kelulut honey (6D-PF) was selected and stored at 4°C for 336 hr (14 d). Changes in the pH, separation behavior, particle characteristics, zeta potential and apparent viscosity were monitored and compared with a positive control containing 10% caramel syrup (Table 5). As the formulation was selected following ambient stability screening, baseline values (0 hr) represented the initial physicochemical state prior to storage and served as the reference for subsequent measurements.

During chilled storage, the 6D-PF system exhibited gradual physicochemical evolution, with a progressive decrease in pH over time, indicating ongoing acidification, which was slightly more pronounced than in the control system. This reduction in pH was accompanied by moderate increases in the particle size and apparent viscosity, along with a slight rise in PDI that remained within a relatively narrow distribution range. The magnitude of  $\zeta$  became less negative during storage, suggesting a gradual reduction in electrostatic repulsion between dispersed particles (Pan et al., 2025). In line with these changes, no visible phase separation was observed at 72 hr, while limited separation (12%) occurred after 336 hr, comparable to the control (Fig. 3).

Despite the absence of abrupt changes in viscosity or particle size, the observed trends were consistent with ongoing aggregation within the colloidal system. The relatively low PDI values indicated that aggregation proceeded slowly, reflecting gradual structural reorganization rather than heterogeneous flocculation. Such behavior is a characteristic of a system undergoing slow physicochemical transitions under refrigerated conditions (Raval et al., 2019).



**Fig. 3** Separation index at 72 hr (left) and 336 hr (right) during chilled storage (4°C) of: (A) pasteurized full-cream milk added with 6% dehumidified Kelulut honey; (B) control (10% caramel syrup addition), where both samples were fully homogeneous at 72 hr and exhibited similar separation (12%) after 336 hr

**Table 5** Physicochemical parameters (pH, zeta potential (ZP), particle size distribution (PSD), polydispersity index (PDI) and apparent viscosity (AV)) of 6D-PF and positive control after 72 hr and 336 h storage at 4°C

| Treatment   | Storage time (hr) | pH                     | PDI                    | PSD (nm)                | ZP (mV)                   | AV (mPa.s)        |
|-------------|-------------------|------------------------|------------------------|-------------------------|---------------------------|-------------------|
| 6D-PF       | 0                 | 5.5±0.00 <sup>a</sup>  | 0.24±0.1 <sup>a</sup>  | 246.7±3.1 <sup>a</sup>  | -29.16±0.15 <sup>ab</sup> | 4.93 <sup>a</sup> |
|             | 72                | 5.41±0.00 <sup>b</sup> | 0.21±0.05 <sup>b</sup> | 250.0±1.00 <sup>a</sup> | -30.76±0.71 <sup>b</sup>  | 5.91 <sup>b</sup> |
|             | 336               | 4.90±0.05 <sup>c</sup> | 0.31±0.00 <sup>c</sup> | 289.0±1.00 <sup>b</sup> | -25.03±0.30 <sup>c</sup>  | 8.41 <sup>c</sup> |
| (+) Control | 0                 | 6.0±0.10 <sup>a</sup>  | 0.24±0.0 <sup>a</sup>  | 276.8±1.9 <sup>a</sup>  | -29.86±0.15 <sup>a</sup>  | 6.00 <sup>a</sup> |
|             | 72                | 5.94±0.05 <sup>b</sup> | 0.18±0.00 <sup>b</sup> | 277.0±1.00 <sup>a</sup> | -35.70±0.81 <sup>b</sup>  | 9.29 <sup>b</sup> |
|             | 336               | 5.44±0.05 <sup>c</sup> | 0.24±0.05 <sup>a</sup> | 287.0±3.00 <sup>b</sup> | -28.67±0.93 <sup>c</sup>  | 12.8 <sup>c</sup> |

6D-PF = pasteurized full cream milk + 6% dehumidified Kelulut honey; Positive (+) control = ultra-high temperature milk with 10% caramel syrup. .

Values (mean ± SD,  $n = 3$ ) with different letters within each parameter and treatment are significantly ( $p < 0.05$ ) different.

Baseline (0 h) values correspond to initial measurements prior to storage and are shared with ambient storage baseline (Table 4).

The pH decreases from 5.5 to 4.9 reflected that the system was in proximity to the casein isoelectric region (pH 4.6–4.8) (Dalglish and Corredig, 2012), where the net charge on casein micelles is markedly reduced and attractive interactions become increasingly dominant. Under these conditions, the system becomes progressively more susceptible to aggregation and phase separation over time, contributing a transition toward a less stable colloidal state (Sadiq et al., 2021).

However, the extent of macroscopic destabilization remained limited within the observed storage period. Both the 6D-PF system and the control exhibited similar separation behavior, with no visible phase separation at 72 hr and only slight separation (12%) after 336 hr. This suggests that, although structural changes at the colloidal level progressed during storage, their macroscopic manifestation remained comparable between treatments under the tested conditions (Ganser et al., 2020).

Within this context, the role of dehumidified Kelulut honey appears to be associated with reducing the progression of physicochemical changes, particularly through its influence on acidification behavior, rather than preventing aggregation entirely. This effect is consistent with differences in water activity and compositional characteristics relative to raw honey (Chen et al., 2021).

## Conclusion

The feasibility was demonstrated of formulating a milk-Kelulut honey beverage using 6% (v/v) dehumidified Kelulut honey in pasteurized full-cream milk, with improved resistance to rapid destabilization compared to raw honey systems. During refrigerated storage at 4°C, the formulation maintained a homogeneous dispersion without visible phase separation for up to 72 hr with only slight separation (12%) after 14 d, accompanied by gradual changes in pH (from 5.5 down to 4.9), particle size and apparent viscosity.

These findings indicated that the system retained short-term kinetic stability, characterized by controlled protein interactions and the absence of gelation within the observed period. However, there was a progressive decrease in pH toward 4.9 after 14 d of storage, resulting in increasingly favorable conditions for aggregation. In this context, the system underwent a transition toward a less stable colloidal state during extended storage.

Accordingly, the stability of the formulation is best interpreted within a defined storage window, in which acceptable dispersion characteristics are maintained prior to the onset of

more pronounced destabilization. This is particularly relevant to ready-to-serve milk-based beverages, which typically are intended for immediate or short-term consumption following preparation.

The improved performance of dehumidified honey was attributed to its reduced moisture content and lower acidification than in the tested raw honey systems, which delayed pH-driven casein aggregation. Within these constraints, the formulation demonstrated practical potential as a clean-label milk-honey beverage with short-term refrigerated applicability. Further microbiological and sensory evaluations are required to establish the full commercial shelf-life and consumer acceptability.

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## Conflict of Interest

The authors declare that there are no conflicts of interest.

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