Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Development and Performance Evaluation of a Vacuum-Assisted Stirred Dehumidification Machine for Stingless Bee Honey

Thanakon Saetaiw
Princess of Naradhiwas University
Wasan Palasai
Princess of Naradhiwas University
Prapaipis Tawonsri
Princess of Naradhiwas University
Hafnee Lateh
Princess of Naradhiwas University
Sabree Sanor
Princess of Naradhiwas University
Thanaset Thongsaiklaing
Princess of Naradhiwas University
Ni-oh Puzu
nioh.p@pnu.ac.th
Princess of Naradhiwas University

Research Article

Keywords: Stingless bee honey, Honey dehumidification, Vacuum drying, Drying kinetics, Thermal efficiency

Posted Date: September 28th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10610585/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Development and Performance Evaluation of a Vacuum-Assisted Stirred Dehumidification Machine for Stingless Bee Honey

Thanakon Saetaiw[1], Wasan Palasai[1], Prapaipis Tawonsri[1], Hafnee Lateh[1], Sabree Sanor[2], Thanaset Thongsaiklaing[3], Ni-oh Puzu[1*]

[1]Department of Mechanical Engineering, Faculty of Engineering, Princess of Naradhiwas University, Narathiwat, 96000, Thailand

[2]Department of Mechanical Engineering, Faculty of Engineering, Princess of Naradhiwas University, Narathiwat, 96000, Thailand

[3]Faculty of Agriculture, Princess of Naradhiwas University, Narathiwas, 96000, Thailand

*Corresponding author e-mail; nioh.p@pnu.ac.th

Abstract

Stingless bee honey is a premium natural product with high nutritional and medicinal value; however, its naturally high moisture content (30–35%) promotes microbial fermentation, shortens shelf life, and restricts commercial production. This study presents the development of a compact vacuum-assisted dehumidification machine integrated with a drying-time prediction model for community-scale stingless bee honey processing. The system combines indirect hot-water heating, vacuum evaporation, and mechanical agitation to accelerate moisture removal while maintaining stable operating conditions. Drying experiments were conducted using 10 L of a honey-like sugar solution with an initial moisture content of 35%, targeting a final moisture content of 20%. The effects of heating temperature (50 and 70 °C), operating pressure (0 and -80 kPa), and agitation speed (0 and 60 rpm) on drying performance were investigated. Moisture content, soluble solids (°Brix), thermal efficiency, electrical energy consumption, and drying time were determined. Drying kinetics were analyzed using Newton's drying equation, and an empirical regression model was established to predict drying time under different operating conditions. Vacuum pressure was identified as the dominant factor governing moisture removal, followed by heating temperature and agitation speed. The optimum condition (70 °C, -80 kPa, and 60 rpm) reduced the moisture content from 35% to 20% within 9 h, whereas 168 h was required under atmospheric pressure at 50 °C without agitation. Soluble solids increased from 64 to 79 °Brix during dehydration. Vacuum operation improved thermal efficiency by 4.21-7.76 times and reduced electrical energy consumption to 0.12-0.14 USD kg^{-1}. The proposed machine and predictive model provide an energy-efficient and practical solution for producing high-quality stingless bee honey and support process design, optimization, and scale-up for community enterprises.

Keywords: Stingless bee honey; Honey dehumidification; Vacuum drying; Drying kinetics; Thermal efficiency.

1. Introduction

Stingless bees have become economically important insects, generating substantial income for farmers. Beyond their economic value, they play a vital role as pollinators in tropical ecosystems, contributing significantly to ecosystem sustainability [1-3]. They also produce high-value products, particularly stingless bee honey, which is recognized for its outstanding nutritional value and medicinal properties. Its physicochemical characteristics, including moisture content, soluble solids, acidity, and hydroxymethylfurfural (HMF), have been widely reported [4-5]. Stingless bee honey is characterized by its distinctive sweet–sour taste and contains abundant phenolic compounds and flavonoids with strong antioxidant and anti-inflammatory activities [6-8]. However, despite these beneficial properties, one of its major limitations is its naturally high moisture content, typically ranging from 30% to 35%. Such high moisture content promotes the growth of yeasts and molds, leading to fermentation and rapid quality deterioration [5], [9-13]. Therefore, reducing the moisture content is essential for preserving the quality of stingless bee honey and represents an important processing technology for increasing its commercial value and promoting Thai agricultural products to international standards.

The naturally high moisture content of stingless bee honey (30-35%) directly accelerates microbial fermentation and quality deterioration [5], [12-14]. Consequently, the development of an efficient dehumidification process is essential to preserve its nutritional value, antioxidant capacity, and phenolic compounds [7], [15]. Various dehydration technologies have been investigated, including vacuum drying [16-19], microwave heating [20-21], low-temperature drying under atmospheric conditions [22-23], rotary-spray honey dehydrators [24], vacuum drying combined with mechanical agitation [25], and polymer-based desiccant dehumidification systems [26]. These technologies not only reduce the moisture content of stingless bee honey but also extend its shelf life while maintaining its physicochemical stability.

A major challenge faced by commercial stingless bee honey producers is the high moisture content, which increases the risk of fermentation and product spoilage [11]. Although industrial-scale dehumidification technologies are available, they are generally large, expensive, and excessively complex for community enterprises. In contrast, small-scale dehumidification systems often lack precise temperature control, and excessive heating may increase hydroxymethylfurfural (HMF) formation and degrade honey quality [27]. Furthermore, the viscosity of honey increases during water evaporation, reducing heat-transfer efficiency and prolonging the drying process [28-29]. Therefore, developing a dehumidification system that integrates efficient heating, pressure reduction to lower the boiling point of water, and mechanical agitation to increase the liquid surface area is a promising approach for accelerating moisture removal. A high-performance dehumidification machine with stable temperature control and reasonable operating costs is therefore essential for enabling community enterprises to produce high-quality stingless bee honey and enhance consumer confidence in standardized products [2-3], [8-9].

Therefore, this study aimed to develop and evaluate a dehumidification machine suitable for community-scale stingless bee honey production. The effects of heating temperature (50 and 70 °C), operating pressure (0 and -80 kPa), and agitation speed (0 and 60 rpm) on the moisture removal rate and quality of stingless bee honey were

systematically investigated. The proposed system was designed to provide stable temperature control, high dehumidification efficiency, and practical operating costs, thereby enabling producers to obtain stingless bee honey with consistent quality, extended shelf life, and improved commercial value that meets international standards.

2. Materials and Methods

2.1 Development of the Stingless Bee Honey Dehumidification Machine

A laboratory-scale honey dehumidification machine with a processing capacity of 10 L consists of a double-jacketed vessel, a vacuum pump, an agitator, a temperature control system, and auxiliary components. A ULVAC YTP400-4W01 vacuum pump was used to remove air and water vapor from the vessel (not shown in Fig. 1). Agitation was provided by an ORIENTAL MOTOR (OM) BHM62T-G2, while the hot-water temperature was controlled using a Panasonic KT4R temperature controller at the desired operating temperatures of 50 and 70 °C, as shown in Fig. 1(a).

The double-jacketed vessel comprised an outer and an inner tank, both fabricated from stainless steel 304. The outer tank served as the hot-water jacket and has an outer diameter of 550 mm, an inner diameter of 400 mm, and a height of 230 mm. It supplied thermal energy to the inner tank through indirect heat transfer. The inner tank was designed with a wide and shallow geometry, having a diameter of 400 mm and a height of 150 mm. The resulting surface-area-to-volume ratio was 12.5664 m^2/m^3, providing a large exposed liquid surface that promoted moisture evaporation during the dehydration process. It is supported by stainless-steel 304 tubular legs with a diameter of 40 mm and a length of 150 mm, as illustrated in Fig. 1(b). Heating was provided by two 300-W stainless-steel cartridge heaters. The hot-water temperature was regulated using a PID controller coupled with Type-T thermocouples to monitor the temperatures of both the hot water and the honey-like sugar solution. The agitator and speed controller were integrated into the top cover assembly, allowing the agitation speed to be adjusted continuously up to a maximum of 100 rpm, as shown in Fig. 1(c). The vessel lid was fabricated from stainless steel 304 with an outer diameter of 230 mm and was used to seal the system during both atmospheric and vacuum operations. It incorporates a stainless-steel vacuum pipe with a diameter of 40 mm and a length of 1000 mm, connecting the vessel to the vacuum pump for air evacuation. A 1/2-inch brass ball valve was installed for sample collection during the dehumidification process. The operating pressure inside the vessel was measured using a KEYENCE AP-44 pressure sensor with a measurement range of 101.3 to -101.3 kPa. In addition, the lid was equipped with a stainless-steel vent valve and a 40-mm-diameter sight glass for visual observation during operation, as shown in Fig. 1(d). The specifications of the machine were summarized in Table 1.

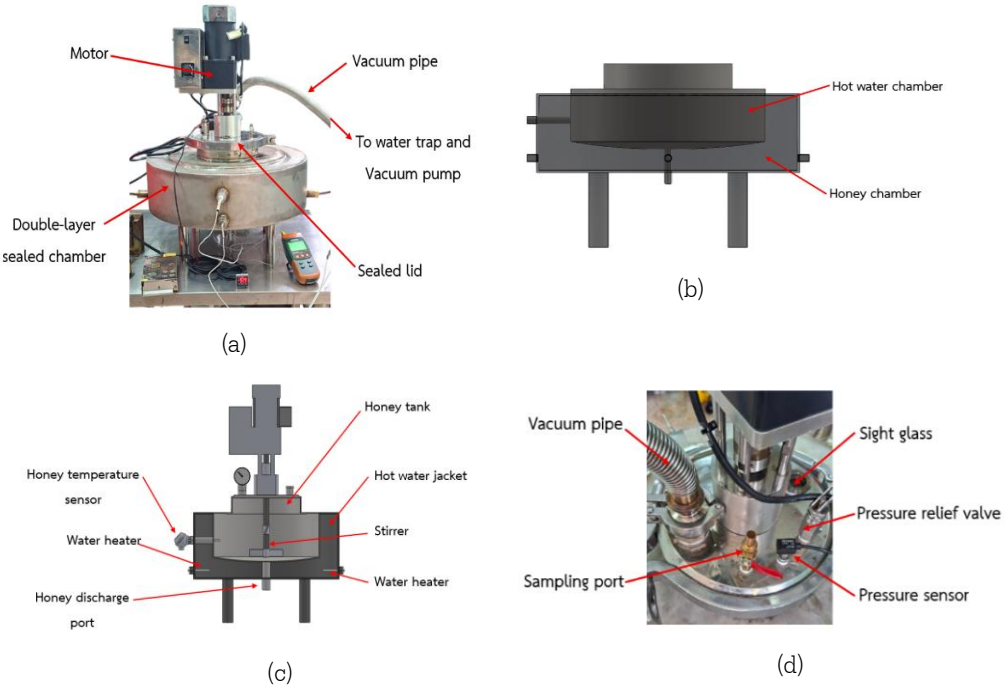


Fig. 1. Configuration of the stingless bee honey dehumidification machine: (a) overall view of the dehumidification machine; (b) double-jacketed vessel; (c) internal configuration of the dehumidification machine; and (d) vessel lid assembly.

Table 1. Specifications of the stingless bee honey dehumidification machine.

Item	Details
Operating principle	Indirect hot-water heating combined with vacuum evaporation and mechanical agitation
Honey capacity	10 L
Hot-water capacity	4.5 L
Operating temperature	50°C to 70°C
Operating Pressure	0 to -80 kPa
Agitation speed	0 to 100 RPM
Heating system	Cartridge electric heaters, 300 W x 2
Vacuum system	Oil Rotary vacuum pump
Temperature controller	PID controller
Construction material	Stainless Steel 304
Overall dimensions	63 x 63 x 75 cm
Surface area-to-volume ratio (m^2/m^3)	12.5664

2.2 Raw Material Preparation

A honey-like sugar solution was prepared as a substitute for stingless bee honey in order to minimize the experimental cost while maintaining moisture characteristics comparable to those of natural honey. The solution was prepared by dissolving brown sugar in water to obtain a total volume of 10 L with an initial moisture content of 35%, representing the upper limit of the moisture content typically found in freshly harvested stingless bee honey [9,10].

The required proportions of brown sugar and water were calculated to achieve the target moisture content. The prepared solution was thoroughly mixed before each experiment to ensure a homogeneous composition. The use of a honey-like sugar solution instead of natural stingless bee honey significantly reduced material consumption and experimental cost while providing consistent experimental conditions throughout the study. A comparison between natural stingless bee honey and the prepared honey-like sugar solution is presented in Fig. 2.



Fig. 2. Natural stingless bee honey and the honey-like sugar solution used in the experiments.

2.3 Experimental Procedure

The experiment was initiated by preparing 10 L of a honey-like sugar solution with an initial moisture content of 35%, as measured using a digital honey moisture meter based on the refractive index principle. Once the hot-water temperature reached the preset value, the honey-like sugar solution was transferred into the jacketed vessel, and the lid was securely closed. The agitator and vacuum pump were then operated simultaneously according to the prescribed experimental conditions. During each experiment, samples of the honey-like sugar solution were collected at 1-h intervals to monitor changes in moisture content and soluble solids (°Brix) throughout the drying process. The experiment was terminated when the moisture content reached the target value of 20%.

Measurement errors and instrument uncertainties directly influence the accuracy of process control and experimental conditions. Therefore, to ensure the reliability and transparency of the experimental results, all data presented in this study were obtained directly from the measuring instruments without correction. The specifications, resolutions, and measurement uncertainties of the instruments used in this study are summarized in Table 2.

Table 2. Measuring instruments and their specifications.

Parameter	Measuring Instruments	Resolution	Error Value (%)
Water Temperature (°C)	Thermocouple Type T	0.1 °C	±0.1
Honey Temperature (°C)	Thermocouple Type T	0.1 °C	±0.1
Pressure (kPa)	Sensor KEYENCE AP-44	0.1 kPa	±0.1
Moisture (%)	Refractive measurement device	0.1 %	±0.2

2.4 Experimental Design

A full-factorial experimental design was employed to investigate the effects of the three primary operating variables on the dehumidification performance of the developed honey dehumidification machine. The investigated factors included heating temperature (50 and 70 °C), operating pressure (0 and -80 kPa), and agitation speed (0 and 60 rpm). Each factor was evaluated at two levels, resulting in eight experimental conditions. The experimental combinations were designated using the notation A, B, and C, representing temperature, pressure, and agitation speed, respectively. This factorial design enabled the individual and combined effects of the operating parameters on moisture removal, drying time, soluble solids, thermal efficiency, and electrical energy consumption to be systematically evaluated. All experiments were conducted using 10 L of honey-like sugar solution with an initial moisture content of 35%, and the dehumidification process was terminated when the moisture content reached 20%. The experimental design and operating conditions are summarized in Table 3.

Table 3. Experimental design and operating conditions for the dehumidification experiments

Condition	Temp. (°C)	P (kPa)	N (rpm)
A1B1C1	50	0	0
A1B1C2	50	0	60
A1B2C1	50	-80	0
A1B2C2	50	-80	60
A2B1C1	70	0	0
A2B1C2	70	0	60
A2B2C1	70	-80	0
A2B2C2	70	-80	60

2.5 Electricity Cost Analysis

The electricity cost of the dehumidification process was evaluated to assess the operating cost of the developed machine under different experimental conditions. The electricity cost per unit mass of the processed honey-like sugar solution was calculated using Eq. (1):

$$\text{Electricity cost } (\text{USD/kg}) = \frac{P \times t \times C_e}{m} \quad (1)$$

where P is the total electrical power consumption of the dehumidification system (kW), including the heater, vacuum pump, and agitator; t is the operating time (h); C_e is the electricity price (USD/kWh); and m is the mass of the processed honey-like sugar solution (kg). This parameter was used to compare the economic performance of the dehumidification process under different operating temperatures, pressures, and agitation speeds.

2.6 Experimental Uncertainties

Experimental uncertainties were evaluated to ensure the reliability of the measured data. The uncertainty of each measuring instrument was obtained from the manufacturer's specifications and considered during data analysis. Temperature was measured using a digital thermometer with an accuracy of ±0.1 °C. The operating pressure was monitored using a vacuum gauge with an accuracy of ±1 kPa. Moisture content was determined using a digital refractometer with an accuracy of ±0.2 °Brix, while electrical power consumption was recorded using a power meter with an accuracy of ±1% of the measured value. The mass of the honey-like sugar solution was measured using an electronic balance with a readability of ±0.01 kg.

3. Results and Discussion

3.1 Moisture Content Variation

Fig. 3 illustrates the variation in the moisture content of the honey-like sugar solution under different heating temperatures (50 and 70 °C), operating pressures (0 and -80 kPa), and agitation speeds (0 and 60 rpm). The experimental results showed that temperature significantly affected the moisture removal rate. Drying at 70 °C exhibited a substantially faster reduction in moisture content than drying at 50 °C, resulting in a shorter drying time. Under vacuum conditions (-80 kPa), the moisture content decreased from 35% to 20% within 9 h at 70 °C, whereas 28 h were required at 50 °C. During the initial stage of drying, moisture content decreased rapidly; however, the evaporation rate gradually declined with increasing drying time because the viscosity of the honey-like sugar solution increased as water was removed. These results indicate that temperature is one of the major factors influencing the moisture removal rate [16], [23], [30]. In addition, vacuum operation enhanced the effect of temperature by accelerating moisture evaporation and further reducing the drying time compared with atmospheric pressure [18], [21].

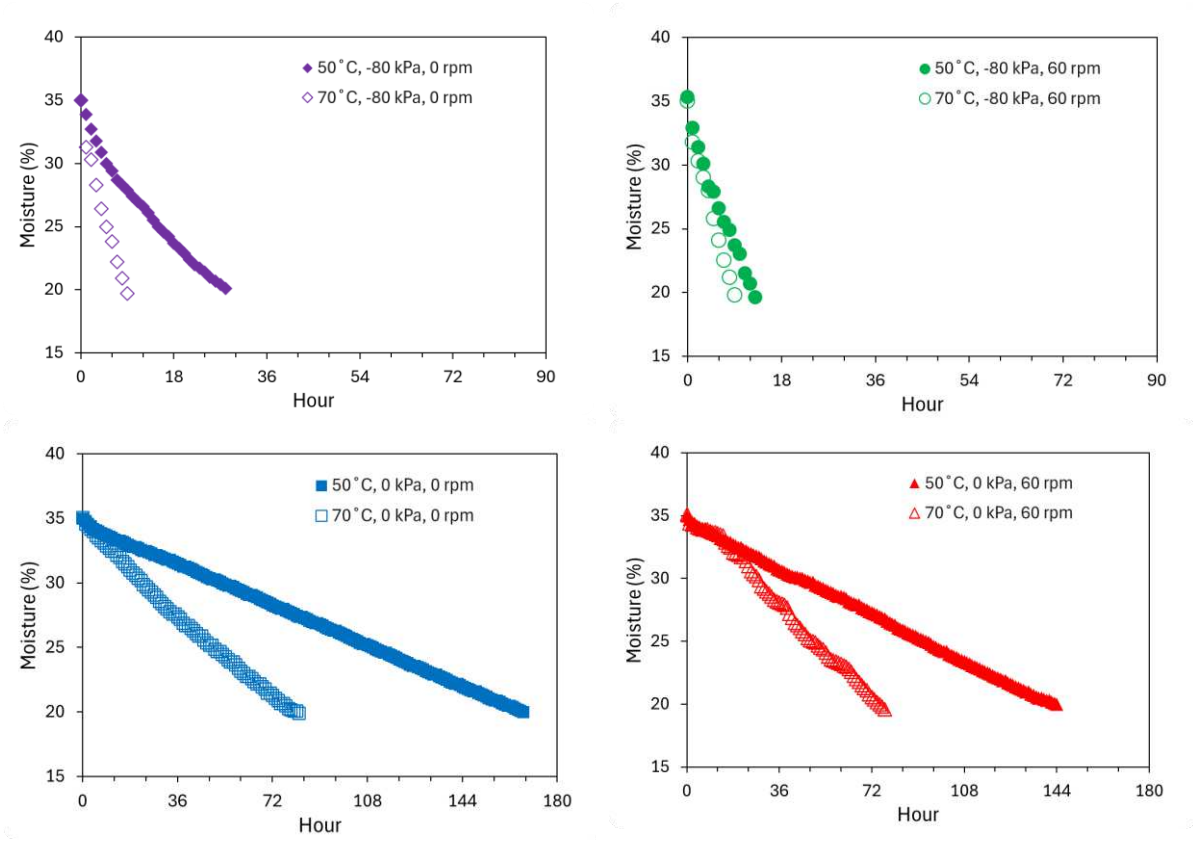


Fig. 3. Variation in the moisture content of the honey-like sugar solution during dehumidification at different temperatures under atmospheric and vacuum conditions.

Fig. 4 presents the effect of operating pressure on the moisture removal behavior of the honey-like sugar solution. A substantial improvement in the drying rate was observed under vacuum conditions (-80 kPa) compared with atmospheric pressure (0 kPa). Under vacuum operation, the moisture content decreased rapidly during the initial stage of drying, enabling the moisture content to be reduced from 35% to 20% within a considerably shorter period. The enhanced drying performance under vacuum conditions is primarily attributed to the reduction in the boiling point of water as the operating pressure decreases. Consequently, moisture evaporation occurred at a lower temperature, allowing water to vaporize more readily without requiring excessive thermal energy. In addition, the pressure difference between the liquid surface and the surrounding environment increased the vapor pressure driving force, thereby accelerating mass transfer from the honey solution to the vapor phase. Similar observations have been reported in previous studies on vacuum drying of honey and other heat-sensitive food materials [18,23].

Compared with atmospheric pressure, vacuum operation not only reduced the drying time but also minimized prolonged thermal exposure, which is advantageous for preserving the physicochemical quality of stingless bee honey. These findings indicate that operating pressure is the dominant factor governing the moisture removal process in the developed dehumidification system.

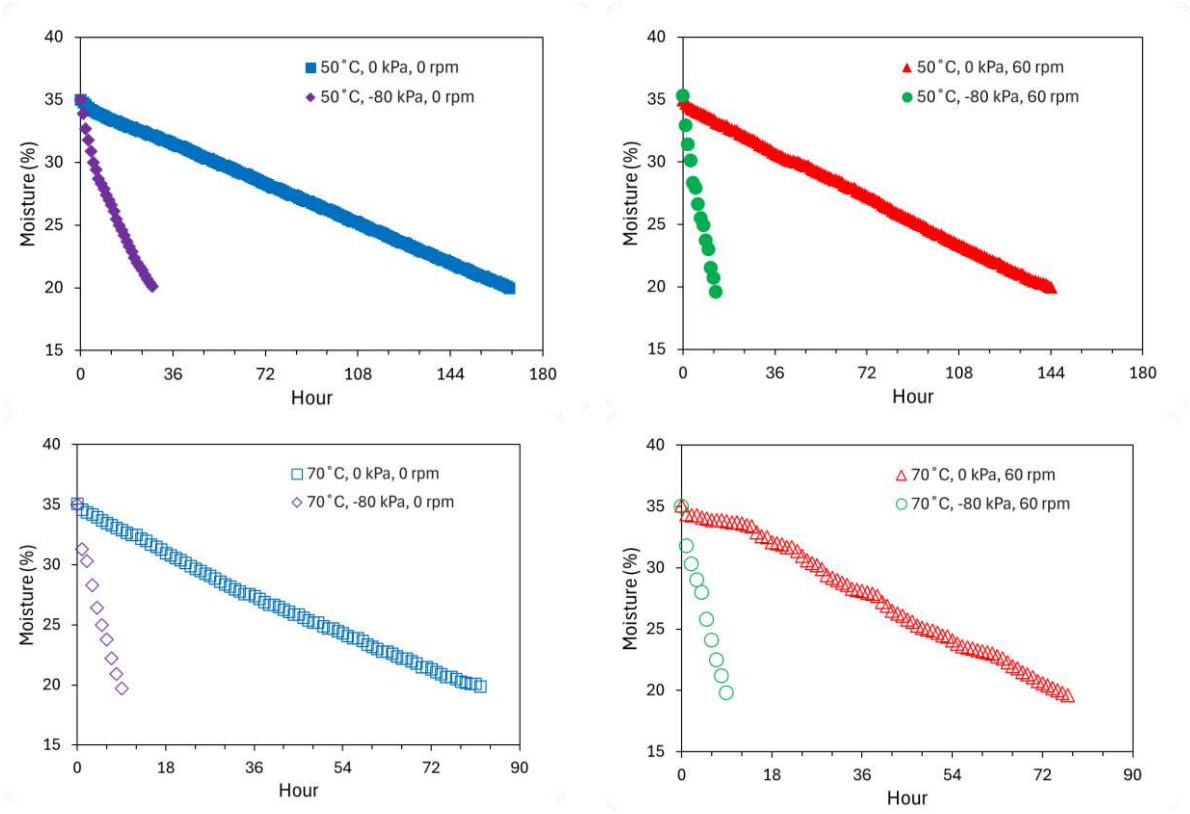


Fig. 4. Effect of operating pressure on the moisture content of the honey-like sugar solution during the dehumidification process.

Fig. 5 illustrates the influence of agitation speed on moisture removal during the dehumidification process. Increasing the agitation speed from 0 to 60 rpm shortened the drying time under all operating conditions. The improvement was particularly noticeable under vacuum conditions, where the combined effects of agitation and pressure reduction produced the highest drying performance. Mechanical agitation continuously renewed the liquid surface exposed to evaporation while promoting uniform temperature distribution throughout the honey solution. Consequently, temperature gradients inside the chamber were reduced, and both heat and mass transfer were enhanced. Agitation also prevented the formation of localized high-viscosity regions near the heating surface, thereby reducing internal diffusion resistance and facilitating moisture transport from the bulk liquid to the evaporation surface.

Although the influence of agitation was less pronounced than those of temperature and operating pressure, it consistently improved drying performance by increasing the effective heat-transfer area and reducing the boundary-layer thickness adjacent to the liquid surface. Similar improvements in drying efficiency due to mechanical mixing have been reported for vacuum-assisted dehydration processes of viscous food products [23,29]. The combined application of elevated temperature, vacuum pressure, and mechanical agitation provided the highest moisture removal rate, confirming that simultaneous enhancement of heat transfer and mass transfer is essential for efficient stingless bee honey dehumidification.

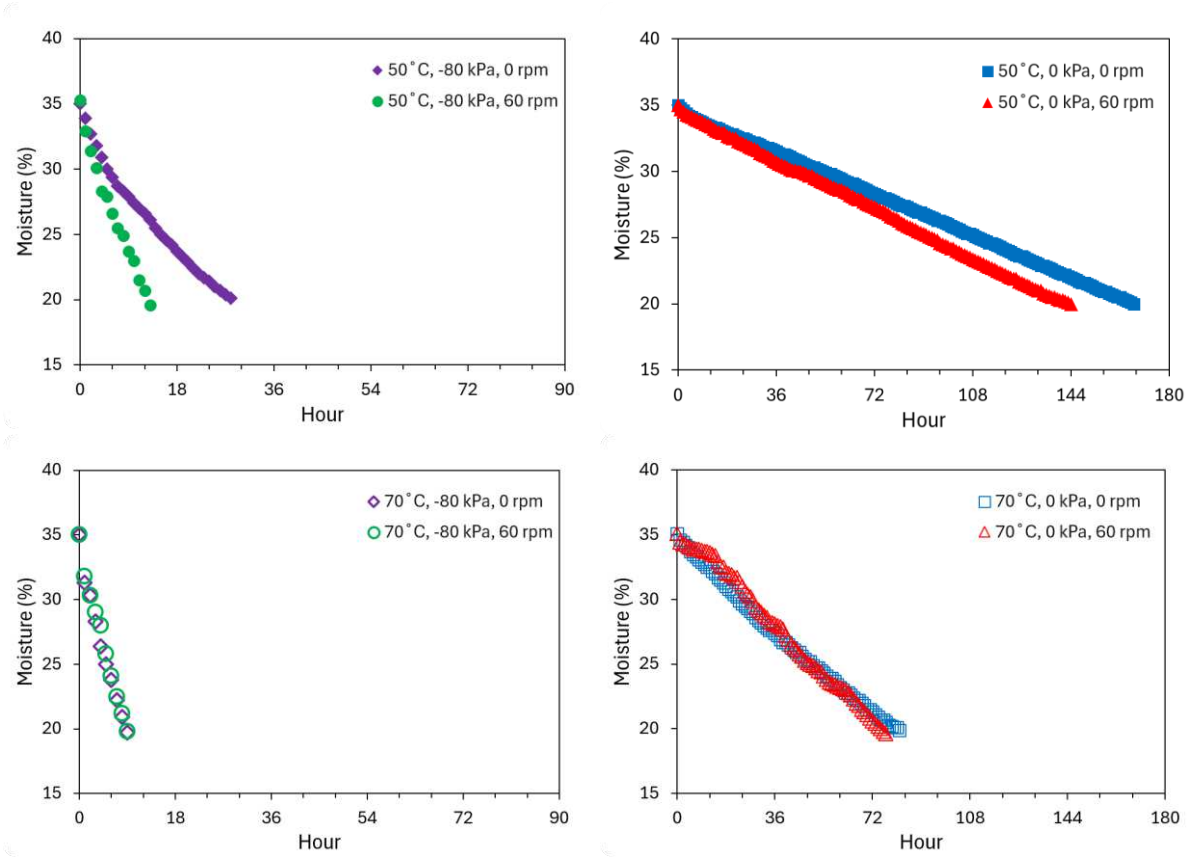


Fig. 5. Effect of agitation speed on the moisture content of the honey-like sugar solution during the dehumidification process.

3.2 Effect of Dehumidification on Soluble Solids Content

Fig. 6 illustrates the variation in the soluble solids content (°Brix) of the honey-like sugar solution during the dehumidification process under different operating temperatures, pressures, and agitation speeds. As the moisture content gradually decreased from 35% to 20%, the soluble solids content increased continuously from approximately 64 to 79 °Brix. This trend indicates that water removal progressively concentrated the dissolved solids in the solution.

Among the investigated operating parameters, vacuum pressure had the greatest influence on the rate of soluble solids concentration. At an operating pressure of -80 kPa, the target soluble solids content was achieved considerably faster than under atmospheric pressure because the reduced pressure promoted moisture evaporation by lowering the boiling point of water. Increasing the operating temperature from 50 to 70 °C further accelerated the concentration process by supplying additional thermal energy for evaporation. Mechanical agitation also contributed to the increase in soluble solids by improving temperature uniformity and enhancing heat and mass transfer within the solution.

The increase in soluble solids content can be explained by the concentration effect resulting from moisture removal. During the dehumidification process, water was continuously evaporated while the amount of

dissolved sugar remained essentially constant. Consequently, the concentration of dissolved solids increased, leading to higher °Brix values. The observed trends demonstrate that the developed dehumidification machine effectively concentrated the model solution by simultaneously enhancing heat transfer and moisture removal. It should be noted that the present study employed a honey-like sugar solution as a model fluid to evaluate the dehumidification performance of the developed machine under controlled and reproducible conditions. Therefore, the measured soluble solids values primarily represent the concentration behavior of the model solution. Validation using natural stingless bee honey is recommended in future studies to confirm the applicability of the developed process to actual honey.

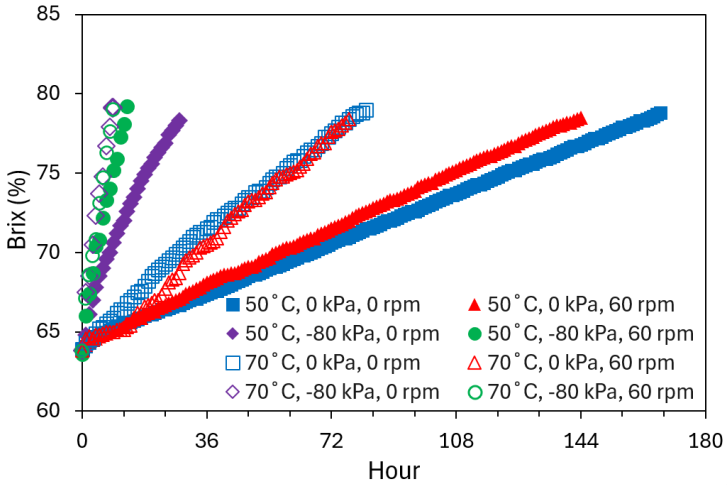


Fig. 6. Variation in the soluble solids content (°Brix) of the honey-like sugar solution during the dehumidification process under different operating conditions.

3.3 Thermal Efficiency

Fig. 7 presents the thermal efficiency of the developed dehumidification machine under different operating temperatures, operating pressures, and agitation speeds. Thermal efficiency was employed to evaluate the effectiveness of electrical energy utilization during the moisture evaporation process.

The results indicate that the dehumidification process under atmospheric pressure (0 kPa) exhibited the lowest thermal efficiency under all operating conditions. When the operating pressure was reduced to -80 kPa, the thermal efficiency increased substantially, reaching values 4.21-7.76 times higher than those obtained under atmospheric conditions. This improvement can be attributed to the reduction in the boiling point of water under vacuum conditions, which accelerates moisture evaporation while requiring less thermal energy. As a result, a larger fraction of the supplied energy is utilized for phase change rather than being dissipated to the surroundings.

Temperature also had a pronounced effect on thermal efficiency. Increasing the operating temperature from 50 °C to 70 °C improved the thermal efficiency by approximately 28.51-72.14%, depending on the pressure and agitation conditions. At the higher temperature, heat was transferred more rapidly from the hot-water jacket

to the honey-like sugar solution, resulting in faster moisture evaporation and a shorter processing time. Agitation further enhanced the process by improving temperature uniformity within the solution, reducing thermal gradients, and facilitating heat transfer throughout the liquid. The highest thermal efficiencies were obtained when vacuum pressure, elevated temperature, and mechanical agitation were applied simultaneously. Under these conditions, moisture was removed more rapidly, reducing both processing time and unnecessary energy consumption. The results suggest that combining these operating parameters is an effective strategy for improving the energy performance of the developed dehumidification machine.

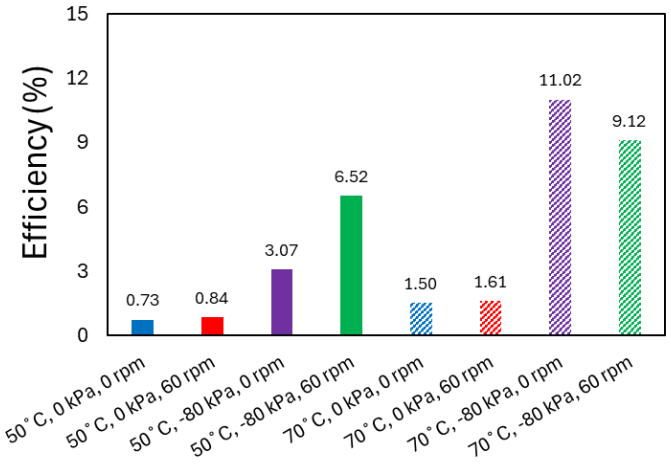


Fig. 7. Thermal efficiency of the developed dehumidification machine under different operating temperatures, pressures, and agitation speeds.

3.4 Electricity Cost

Fig. 8 compares the electricity cost of the dehumidification process under different operating temperatures, pressures, and agitation speeds. The electricity cost is expressed as the electrical energy consumption per kilogram of processed honey-like sugar solution (USD/kg), providing an economic indicator for evaluating the operating performance of the developed dehumidification machine.

The results show that operating under vacuum conditions (-80 kPa) substantially reduced the electricity cost compared with atmospheric pressure (0 kPa). At 70 °C and -80 kPa, the electricity costs were 0.12 USD/kg and 0.14 USD/kg at agitation speeds of 0 and 60 rpm, respectively. Under the same temperature at atmospheric pressure, the corresponding costs increased to 0.65 USD/kg and 0.82 USD/kg. At 50 °C, the electricity costs under vacuum conditions were 0.45 USD/kg and 0.21 USD/kg, whereas atmospheric operation resulted in considerably higher costs of 1.33 USD/kg and 1.53 USD/kg for agitation speeds of 0 and 60 rpm, respectively.

The lower electricity cost achieved under vacuum conditions is mainly attributed to the shorter drying time. Reducing the operating pressure lowers the boiling point of water, allowing moisture to evaporate more readily and thereby decreasing the duration of the dehumidification process. Although the vacuum pump requires

additional electrical power, the reduction in processing time more than compensates for this energy consumption, resulting in a lower electricity cost per unit mass of product. The combined application of vacuum pressure and elevated temperature provided the lowest electricity cost among the investigated operating conditions. These operating conditions improved moisture removal while reducing processing time, making the developed dehumidification machine more economically attractive for practical applications.

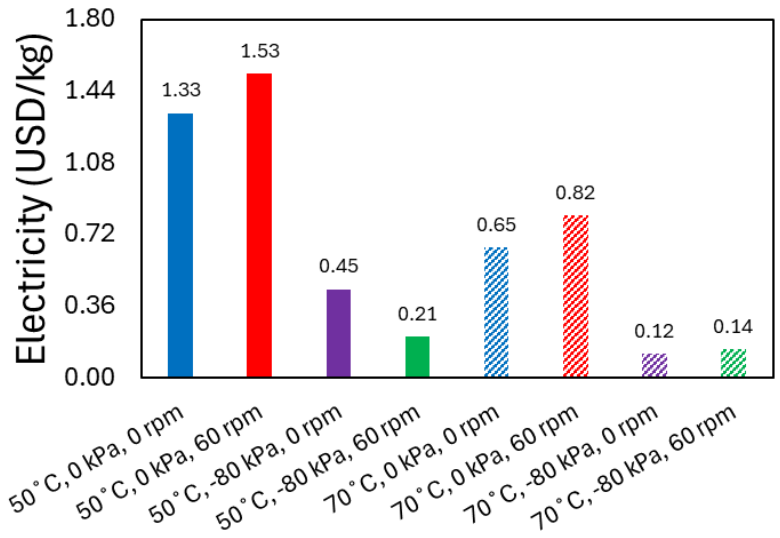


Fig. 8. Electricity cost of the dehumidification process under different operating temperatures, pressures, and agitation speeds.

3.5 Regression analysis and drying-time correlation

The drying behavior of honey under different operating conditions was analyzed using a regression-based drying model. The moisture ratio, MR was defined according to Newton's drying equation as

$$MR = \frac{M}{M_i} = e^{-kt} \tag{2}$$

where M_i and M are the initial and instantaneous moisture contents (%), respectively, t is the drying time (h), and k is the drying constant (h^{-1})

The drying constant for each experimental condition was estimated from the measured drying time required to reduce the moisture content from 35 % to 20 % according to

$$k = \frac{-\ln(M/M_i)}{t} \tag{3}$$

Since the moisture ratio for the present study was

$$\frac{M}{M_i} = \frac{20}{35} = 0.5714 \tag{4}$$

the drying constant becomes

$$k = \frac{0.5596}{t} \quad (5)$$

The estimated drying constants obtained from the experimental data are summarized in Table 4.

Table 4. Effect of temperature, pressure, and agitation speed on the drying time and drying rate constant of stingless bee honey.

Condition	Drying time, t (h)	Drying constant, k (h^{-1})
A1B1C1	168	0.00333
A1B1C2	144	0.00389
A1B2C1	28	0.01999
A1B2C2	13	0.04305
A2B1C1	82	0.00682
A2B1C2	77	0.00727
A2B2C1	9	0.06218
A2B2C2	9	0.06218

The drying constant was correlated with the experimental parameters including honey temperature (T) vacuum pressure (P), and agitation speed (N) using a power-law regression model expressed as

$$k = CT^{a}(|P| + 1)^{b}(N + 1)^{c} \quad (6)$$

To determine the regression coefficients, the equation was linearized by applying the natural logarithm:

$$\ln k = \ln C + a \ln T + b \ln(|P| + 1) + c \ln(N + 1) \quad (7)$$

Regression fitting of the experimental data yielded the following empirical correlation:

$$k = 9.398 \times 10^{-7} T^{2.076}(|P| + 1)^{0.484}(N + 1)^{0.063} \quad (8)$$

The regression model yielded a coefficient of determination of $R^2 = 0.9777$, indicating good agreement between the predicted and experimental values. The exponent values indicate that honey temperature had the strongest influence on the drying rate, followed by vacuum pressure, whereas agitation speed showed a comparatively smaller effect.

Fig. 9 shows the comparison between the experimentally obtained drying constants and the values predicted by the regression model. The predicted values closely follow the experimental data, demonstrating that the proposed correlation can satisfactorily estimate the drying kinetics of honey under different operating conditions.

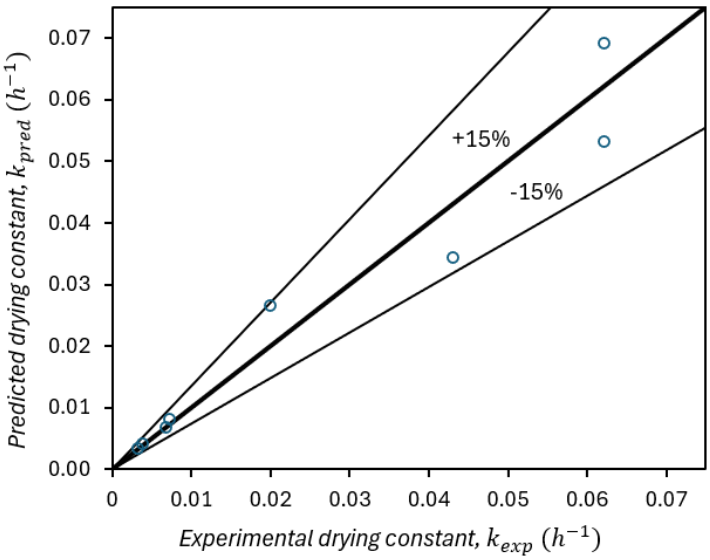


Fig. 9. Comparison between experimental and predicted drying constants obtained from the regression model.

Substituting the obtained drying constant into Newton's drying equation gives the generalized drying-time correlation:

$$t = \frac{-\ln(M/M_i)}{9.398\times10^{-7}T^{2.076}(|P|+1)^{0.484}(N+1)^{0.063}} \tag{10}$$

For the present study, the drying-time equation can be simplified as

$$t = \frac{0.5596}{9.398\times10^{-7}T^{2.076}(|P|+1)^{0.484}(N+1)^{0.063}} \tag{11}$$

For example, under the operating conditions of (70 °C), (-80 kPa), and 60 rpm, the predicted drying time can be calculated as follows:

$$t = \frac{0.5596}{9.398\times10^{-7}70^{2.076}(81)^{0.484}(61)^{0.063}} \tag{12}$$

The predictive capability of the proposed regression model was demonstrated using an operating condition of 70 °C, −80 kPa, and 60 rpm. Under these conditions, the temperature, pressure, and agitation terms were calculated as $(70)^{2.076} = 6746.7$, $(81)^{0.484} = 8.39$, and $(61)^{0.063} = 1.30$ respectively. Substituting these values into Eq. (12) resulted in a predicted drying time of approximately 8.1 h, which was in good agreement with the experimental drying time of approximately 9 h. The close agreement between the predicted and experimental results demonstrates that the proposed regression model is capable of accurately predicting the drying time under the investigated operating conditions.

4. Conclusion

This study developed and evaluated a 10-L vacuum-assisted dehumidification machine for stingless bee honey intended for community-scale production. The effects of temperature, vacuum pressure, and agitation speed on moisture removal, soluble solids, thermal efficiency, energy consumption, and drying time were systematically investigated. In addition, a regression-based predictive model was established to estimate the drying time under different operating conditions. The key findings of this study are summarized as follows:

1. Temperature significantly influenced the moisture removal rate. Operating at 70 °C substantially accelerated moisture reduction compared with 50 °C, resulting in a considerably shorter drying time.

2. Vacuum pressure was identified as the most influential operating parameter. Operating under -80 kPa reduced the boiling point of water and markedly enhanced moisture evaporation compared with atmospheric pressure (0 kPa), thereby significantly shortening the drying time.

3. The optimum operating condition was obtained at 70 °C, -80 kPa, and 60 rpm, reducing the moisture content from 35% to 20% within 9 h. Under atmospheric pressure and lower temperature (50 °C) without agitation, the drying process required up to 168 h. Mechanical agitation contributed to improving heat distribution and reducing drying time under some operating conditions, although its influence was less significant than those of temperature and vacuum pressure.

4. The soluble solids content increased as moisture content decreased. Under vacuum conditions, the soluble solids increased from 64 to 79 °Brix within 9-28 h, demonstrating the direct relationship between moisture removal and honey concentration.

5. Vacuum-assisted drying considerably improved the thermal performance and reduced energy consumption. The thermal efficiency was 4.21-7.76 times higher than that under atmospheric pressure, while the minimum electricity cost was only 0.12-0.14 USD kg^{-1} at 70 °C and -80 kPa.

6. A predictive drying-time model was successfully developed based on Newton's drying equation and regression analysis. The proposed model relates the drying time to the operating temperature, vacuum pressure, and agitation speed as follows:

$$t = \frac{0.5596}{9.398 \times 10^{-7}\, T^{2.076}(|P|+1)^{0.484}(N+1)^{0.063}}$$

where t is the drying time (h), T is the operating temperature (°C), P is the operating pressure (kPa), and N is the agitation speed (rpm). The model showed excellent agreement with the experimental data, with a coefficient of determination of $R^2 = 0.9777$, indicating its suitability for predicting drying time and optimizing the operating conditions of the developed dehumidification system.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Fundamental Fund (FF), Fiscal Year 2025, through the Office of Thailand Science Research and Innovation (TSRI) under the Research and Creative Works Program (Grant No. 03/2568).

Author contributions

T. S., W. P. and N. P. performed investigations, formal analysis, data curation and wrote manuscript. W. P., P. T. and H. L. did data validation. S. S. and T. T. reviewed and edited manuscript draft. N. P. and W. P. provided facilities. T. S. and W. P. were involved in conceptualization and methodology while N. P. also did supervision.

Funding

This work was supported by the Fundamental Fund, Fiscal Year 2025, provided by Thailand Science Research and Innovation, Grant No. 03/2568

Data availability

Data cannot be shared openly but are available on request from authors.

Third party material

All materials are owned by the authors, and no permission is required.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not Applicable.

Dual publication

The results/data/figures in this manuscript have not been published elsewhere, nor are they under consideration.

Competing interests

The authors declare no competing interests.

References

[1] Salgado, F. S., Pereira, G. d. S., Souza, D. d. S., Botina, L. L., Silva, L. L., Martins, J. L. A., Vilela, E. F., Martins, G. F., & Serrão, J. E. (2026). Chlorfenapyr-based insecticide causes multiple side effects on workers of the stingless bee Partamona helleri (Friese, 1900) (Hymenoptera: Apidae). Environmental Pollution, 396, Article 127855. https://doi.org/10.1016/j.envpol.2026.127855

[2] Lippi, I. C. d. C., Schouten, C., Lima, Y. S., Souza, G. D. F. d., Moreira, I. d. R. C., Scheffer, J. d. L., Astolfi, A., & Orsi, R. d. O. (2026). Beyond honey bees: Stingless bees exhibit greater sensitivity to pesticides with implications for risk assessment. Pesticide Biochemistry and Physiology, 217, Article 106837. https://doi.org/10.1016/j.pestbp.2025.106837

[3] Singh, G., Makinson, J. C., Doney, M. F., Nzie, O. P., Cook, J. M., & Spooner-Hart, R. (2026). Australian stingless bees exhibit greater sensitivity to dimethoate than Apis mellifera: Implications for pesticide risk assessment. Pesticide Biochemistry and Physiology, 220, Article 107083. https://doi.org/10.1016/j.pestbp.2026.107083

[4] Zhang, J., Yates, H. S. A., Gomes, C. R. D. A., Nicodemo, D., Fletcher, M. T., Marelli, J. P., & Hungerford, N. L. (2025). Variations in the sugar profiles of Brazilian stingless bee honeys as determined by ion chromatography: A preliminary study of the effect of bee species and botanical source. Journal of Food Composition and Analysis, 148, Article 108187. https://doi.org/10.1016/j.jfca.2025.108187

[5] Mduda, C. A., Hussein, J. M., & Muruke, M. H. (2023). Discrimination of honeys produced by Tanzanian stingless bees (Hymenoptera, Apidae, Meliponini) based on physicochemical properties and sugar profiles. Journal of Agriculture and Food Research, 14, Article 100803. https://doi.org/10.1016/j.jafr.2023.100803

[6] Khongkwanmueang, A., Nuyu, A., Straub, L., & Maitip, J. (2020). Physicochemical profiles, antioxidant and antibacterial capacity of honey from stingless bee Tetragonula laeviceps species complex. E3S Web of Conferences, 141, Article 03007. https://doi.org/10.1051/e3sconf/202014103007

[7] Ng, W. J., Matejczuk, K., Ee, K. Y., Boutrou, I., Hew, P. S., Szweda, P., & Mossialos, D. (2025). Honey bee and stingless bee products: Effects on microbial virulence factors and pathogenicity mechanisms. Journal of Functional Foods, 132, Article 106967. https://doi.org/10.1016/j.jff.2025.106967

[8] Shehata, M. G., Ahmad, F. T., Badr, A. N., Masry, S. H., & El-Sohaimy, S. A. (2020). Chemical analysis, antioxidant, cytotoxic and antimicrobial properties of propolis from different geographic regions. Annals of Agricultural Sciences, 65, 209–217. https://doi.org/10.1016/j.aoas.2020.12.001

[9] Berhanu, S., Tadesse, D. M., & Jorge, A. (2022). Physico-chemical properties of Ethiopian Apis mellifera Honey: Review. International Journal of Agricultural Science and Food Technology, 8(1), 038–044. https://dx.doi.org/10.17352/2455-815X.000143

[10] van Boekel, M. A. J. S. (2023). Moisture content and water activity relations in honey: A Bayesian multilevel meta-analysis. Journal of Food Composition and Analysis, 123, Article 105595. https://doi.org/10.1016/j.jfca.2023.105595

[11] Klaithin, K., Chuttong, B., Hung, Y. T., Peng, C. C., Lin, J. A., Lin, C. F., Hongsibsong, S., Maitip, J., Danmek, K., Punthi, F., & Wu, M. C. (2026). Effect of bee species on the physicochemical, bioactive, and microbiological properties of longan honey in Thailand. Journal of Food Composition and Analysis, 151, Article 108998. https://doi.org/10.1016/j.jfca.2026.108998

[12] Dallagnol, A. M., Lautharte, T. E., Brunetti, A. E., & Isidorov, V. A. (2026). Fructophilic fermentation of honeys from five different neotropical stingless bee species is determined by species-specific differences in lactic acid bacteria. Fermented Foods, 2, Article 100005. https://doi.org/10.1016/j.ferfo.2026.100005

[13] Phonmat, S., Charoenphun, N., Chitov, T., Maitip, J., Ungwiwatkul, S., Phokasem, P., Chiu, C. I., Attasopa, K., Evans, J. D., Chen, Y. P., Disayathanoowat, T., Chantaphanwattana, T., Kanokrung, A., Watanadilok, R., Sinpoo, C., Srisuk, N., Krajangjaeng, B., Nanuam, J., & Krongdang, S. (2025). Comparative analysis of microbiological, physicochemical, antioxidant and antibacterial properties of stingless bee (Tetragonula pagdeni Schwarz) honey from various agricultural areas in Eastern Thailand. Applied Food Research, 5, Article 101183. https://doi.org/10.1016/j.afres.2025.101183

[14] Lastriyanto, A., Wibowo, S. A., Erwan, Jaya, F., Batoro, J., Masyithoh, D., & Lamerkabel, J. S. A. (2020). Moisture reduction of honey in dehumidification and evaporation processes. Journal of Mechanical Engineering Science and Technology, 4(2), 153-163. https://doi.org/10.17977/um016v4i22020p153

[15] Akhmazillah, M. F. N., Farid, M. M., & Silva, F. V. M. (2013). High pressure processing (HPP) of honey for the improvement of nutritional value. Innovative Food Science & Emerging Technologies, 20, 59–63. https://doi.org/10.1016/j.ifset.2013.06.012

[16] Biluca, F. C., Betta, F. D., Oliveira, G. P. d., Pereira, L. M., Gonzaga, L. V., Costa, A. C. O., & Fett, R. (2014). 5-HMF and carbohydrates content in stingless bee honey by CE before and after thermal treatment. Food Chemistry, 159, 244–249. https://dx.doi.org/10.1016/j.foodchem.2014.03.016

[17] Fallico, B., Zappalà, M., Arena, E., & Verzera, A. (2004). Effects of conditioning on HMF content in unifloral honeys. Food Chemistry, 85(2), 305–313. https://doi.org/10.1016/j.foodchem.2003.07.010

[18] Jiamjariyatam, R., Mekkerdchoo, O., Phucharoenrak, P., & Zheng, L. (2024). Effects of freeze-drying and vacuum-drying on the quality, total phenolic contents, and antioxidant activities of bee honey in northern Thailand. AIMS Agriculture and Food, 9(2), 430–444. https://doi.org/10.3934/agrfood.2024025

[19] Tosi, E., Ciappini, M., Re, E., & Lucero, H. (2002). Honey thermal treatment effects on hydroxymethylfurfural content. Food Chemistry, 77, 71–74. https://doi.org/10.1016/S0308-8146(01)00325-9

[20] Hebbar, H. U., Nandini, K. E., Lakshmi, M. C., & Subramanian, R. (2003). Microwave and infrared heat processing of honey and its quality. Food Science and Technology Research, 9(1), 49–53. https://doi.org/10.3136/fstr.9.49

[21] Yegge, M. A., Fauzi, N. A. M., Talip, B. A., Jaafar, M. B., Othman, M. B., Yaacob, M., Ilyas, M. A., & Ngajikin, N. H. (2020). Reduction in moisture content of dehumidified and microwave-heated stingless bee (Kelulut) honey and its quality. Materials Today Proceedings, 42(1), 75–79. https://doi.org/10.1016/j.matpr.2020.09.803

[22] Dang, T. T. N., Pham, D. C., Pham, N. Q., Vu, N. H., Cung, T. T. Q., & Nguyen, M. T. (2021). Evaluation of the novel dehydration concept for wild multi floral honey in Vietnam. Chemical Engineering Transactions, 87, 325–330. https://doi.org/10.3303/CET2187055

[23] Subramanian, R., Hebbar, H. U., & Rastogi, N. K. (2007). Processing of honey: A review. International Journal of Food Properties, 10(1), 127–143. https://doi.org/10.1080/10942910600981708

[24] Morawski, M., Malec, M., & Niezgoda-zelasko, B. (2022). Effective condensing dehumidification in a rotary-spray honey dehydrator. Energies, 15, Article 100. https://doi.org/10.3390/en15010100

[25] Jaya, F., Radiati, L. E., Estiasih, T., Rosyidi, D., Lastriyanto, A., Junus, M., Batoro, J., Erwan, E., Lamerkabel, J. S. A., Masyithoh, D., Ustadi, U., & Pinandita, E. P. (2022). Honey moisture reduction using several thermal methods and their effects on its quality. E3S Web of Conferences, 335, Article 00026. https://doi.org/10.1051/e3sconf/202233500026

[26] Kumar, S., Salins, S. S., & Reddy, S. V. K. (2025). Influence of the velocity ratio and rotational speed on the polymer based desiccant dehumidifier. Discover Applied Sciences, 7, Article 687. https://doi.org/10.1007/s42452-025-07307-4

[27] Althaiban, M. A. (2024). Investigation of hydroxymethylfurfural levels in commercial acacia honey for quality control: A systematic review. Discover Applied Sciences, 6, Article 515. https://doi.org/10.1007/s42452-024-06216-2

[28] Al-Waili, N., Ghamdi, A. A., Ansari, M. J., Al-Attal, Y., Al-Mubarak, A., & Salom, K. (2013). Differences in composition of honey samples and their impact on the antimicrobial activities against drug multiresistant bacteria and pathogenic fungi. Archives of Medical Research, 44(4), 307–316. https://doi.org/10.1016/j.arcmed.2013.04.009

[29] Singh, I., & Singh, S. (2018). Honey moisture reduction and its quality. Journal of Food Science and Technology, 55(10), 3861–3871. https://doi.org/10.1007/s13197-018-3341-5

[30] Mohammed, I., Forsido, S. F., & Kuyu, C. G. (2024). Optimization of barrel temperature and feed moisture content for better physicochemical and sensory properties of extruded snacks from blends of finger millet, sweet potato, and soybean composite flour using response surface methodology. Discover Applied Sciences, 6(4), Article 176. https://doi.org/10.1007/s42452-024-05822-4