

อิทธิพลของเทคนิคการอบแห้งที่แตกต่างกันต่อสารออกฤทธิ์ทางชีวภาพและฤทธิ์ต้านอนุมูลอิสระ
ของใบกระท่อม (*Mitragyna speciosa* (Korth.) Havil): ปริมาณไมทราไจนีน
ในเทคนิคที่เหมาะสมที่ได้รับคัดเลือก

Influence of Different Drying Techniques on Bioactive Compounds and Antioxidant
Activity of Kratom (*Mitragyna speciosa* (Korth.) Havil) Leaves:
Mitragynine Content in the Selected Optimal Technique

จีระนันท์ วงศ์วาทัญญู¹ เกียรติพงษ์ เจริญจิตต์² และ อภิญญา ภูมิสายดอน^{2*}

Jeeranan Wongwatanyoo¹, Kaittipong Chareonjit² and Apinya Bhumsaidon^{2*}

¹คณะศิลปศาสตร์และวิทยาศาสตร์ มหาวิทยาลัยราชภัฏศรีสะเกษ จังหวัดศรีสะเกษ

²คณะเทคโนโลยีการเกษตร มหาวิทยาลัยกาฬสินธุ์ จังหวัดกาฬสินธุ์

¹Faculty of Liberal Arts and Science, Sisaket Rajabhat University, Sisaket Province

²Faculty of Agricultural Technology, Kalasin University, Kalasin Province

*Corresponding Author: apinya.bh@ksu.ac.th

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บทคัดย่อ

การศึกษานี้มีวัตถุประสงค์เพื่อประเมินอิทธิพลของวิธีการอบแห้งที่แตกต่างกันต่อสมบัติทางเคมีและกายภาพ ปริมาณสารฟีนอลิกทั้งหมด และฤทธิ์ต้านอนุมูลอิสระของใบกระท่อม (*Mitragyna speciosa* (Korth.) Havil.) โดยเปรียบเทียบวิธีการอบแห้ง 4 วิธี คือ การตากแดดโดยตรง การอบแห้งด้วยโรงอบแห้งพลังงานแสงอาทิตย์แบบพาราโบลา การอบแห้งด้วยตู้อบลมร้อนแบบถาด และการอบแห้งด้วยโรงเรือนอบแห้งแบบทึบแสง ผลการทดลองพบว่าการอบแห้งทุกวิธีสามารถลดปริมาณความชื้น (8.7 – 10.4 % w.b.) และค่า water activity (a_w) อยู่ในช่วง 0.36 - 0.52 อย่างไรก็ตามพบความแตกต่างอย่างมีนัยสำคัญทางสถิติ ($p \leq 0.05$) ในค่าสีและฤทธิ์ต้านอนุมูลอิสระ โดยวิธีอบแห้งด้วยโรงเรือนอบแห้งแบบทึบแสงให้ค่าปริมาณสารฟีนอลิกทั้งหมดสูงที่สุด ($196.64 \text{ mg GAE g}^{-1}$) และไม่แตกต่างอย่างมีนัยสำคัญ ($p > 0.05$) จากการตากแดดโดยตรง ($195.07 \text{ mg GAE g}^{-1}$) ทั้งนี้ใบกระท่อมที่ผ่านการอบแห้งด้วยโรงเรือนอบแห้งแบบทึบแสงแสดงค่าความเข้มสี (Chroma) และค่ามุมเฉดสี ($^{\circ}h$) ที่สูงกว่า สามารถรักษาค่าความเป็นสีเขียว ($-a^*$) ได้ดีกว่า รวมทั้งยังมีสุขลักษณะในการผลิตที่เหมาะสมกว่าอีกด้วย นอกจากนี้ฤทธิ์ต้านอนุมูลอิสระที่ประเมินด้วยวิธี DPPH และ ABTS⁺ มีค่าสูงสุด (74.03 % และ 97.14 % ตามลำดับ) ภายใต้การอบแห้งด้วยโรงเรือนอบแห้งแบบทึบแสงเช่นกัน เมื่อพิจารณาจากปริมาณสารสำคัญที่ยังคงเหลือและคุณภาพของผลิตภัณฑ์จากการอบแห้งแล้ว วิธีการอบแห้งด้วยโรงเรือนอบแห้งแบบทึบแสงได้รับคัดเลือกสำหรับการวิเคราะห์ปริมาณไมทราไจนีนในขั้นตอนถัดไป โดยใบกระท่อมอบแห้งที่ได้มีปริมาณไมทราไจนีนเท่ากับ 9.83 mg g^{-1} (น้ำหนักแห้ง) อย่างไรก็ตาม เนื่องจากงานวิจัยนี้ทำการวิเคราะห์ปริมาณไมทราไจนีนเฉพาะในวิธีการอบแห้งที่ได้รับการคัดเลือกว่ามีความเหมาะสมที่สุด จึงไม่สามารถสรุปเปรียบเทียบการคงอยู่ของไมทราไจนีนระหว่างวิธีการอบแห้งทั้งหมดได้ โดยผลการศึกษาชี้ให้เห็นว่าการอบแห้งด้วยโรงเรือนอบแห้งแบบทึบแสงเป็นแนวทางที่เหมาะสม สามารถรักษาสารออกฤทธิ์ทางชีวภาพและฤทธิ์ต้านอนุมูลอิสระที่สำคัญไว้ได้ และประหยัดพลังงานสำหรับการแปรรูปใบกระท่อมอบแห้งในระดับชุมชน

คำสำคัญ: ใบกระท่อม, ไมทราไจนีน, โรงเรือนอบแห้งแบบทึบแสง, ฤทธิ์ต้านอนุมูลอิสระ, สารฟีนอลิกทั้งหมด

Abstract

This study aimed to evaluate the influence of different drying methods on the chemical and physical properties, total phenolic content (TPC), and antioxidant activity of kratom (*Mitragyna speciosa* (Korth.) Havil.) leaves. Four drying techniques were compared: direct sunlight drying, parabolic solar drying, hot-air tray drying, and opaque greenhouse drying. The results showed that all drying methods effectively reduced moisture content (8.7–10.4 % w.b.) and water activity (a_w) values ranging from 0.36 to 0.52. However, significant differences ($p \leq 0.05$) were observed in color parameters and antioxidant activity among treatments. Opaque greenhouse drying yielded the highest TPC (196.64 mg GAE g⁻¹), which was not significantly different ($p > 0.05$) from direct sunlight drying (195.07 mg GAE g⁻¹). Nevertheless, leaves dried using the opaque greenhouse drying exhibited higher color intensity (chroma), a greater hue angle (h°), improved retention of greenness (-a*), and improved hygienic conditions. Antioxidant activity, evaluated by DPPH and ABTS⁺ assays, was also highest under opaque greenhouse drying (74.03% and 97.14%, respectively). Based on the retention of bioactive compounds and overall product quality, opaque greenhouse drying was selected for subsequent mitragynine analysis, yielding a content of 9.83 mg g⁻¹ (dry weight). However, since mitragynine was quantified only in the selected optimal treatment, direct comparisons of mitragynine retention among all drying methods could not be established. Collectively, the results suggest that opaque greenhouse drying offers a practical, preserves key bioactive compounds and antioxidant activity, and energy-efficient solution for community-scale kratom processing.

Keywords: Kratom leaves, Mitragynine, Opaque greenhouse dryer, Antioxidant activity, Total phenolic content

1. Introduction

Kratom (*Mitragyna speciosa* (Korth.) Havil.) is a tropical medicinal plant indigenous to Southeast Asia that has been traditionally utilized for its analgesic, anti-inflammatory, hypolipidemic, and stimulant-related properties (Nawaka et al., 2025; Singh et al., 2019; Hossain et al., 2023; Sornsenee et al., 2025). Recent scientific investigations have demonstrated that kratom leaves are a rich source of bioactive phytochemicals, including polyphenols, flavonoids, and indole alkaloids—most notably mitragynine—which contribute significantly to their antioxidant and anti-inflammatory activities (Eastlack et al., 2020). Mitragynine, the most abundant alkaloid in kratom, has been reported to range from 0.7% to 38.7% in traditional and commercial kratom products (Sharma et al., 2019), and from 7.5 to 26.6 mg g⁻¹ dry leaf weight in kratom leaves (Leksungnoen et al., 2022). As global demand for kratom-based products continues to rise, ensuring consistent quality and bioactive compound retention during postharvest processing has become increasingly important.

Drying is a critical postharvest operation for kratom leaves due to their susceptibility to enzymatic degradation, microbial growth, and phytochemical loss. In medicinal plants, drying conditions can markedly influence phenolic retention, antioxidant capacity, and color stability (Arslan & Özcan, 2011; Puranik et al.,

2012). Therefore, four drying methods were selected to represent contrasting thermal and environmental conditions commonly used in practice. Open-sun drying (direct sunlight) was included as a traditional, low-cost approach characterized by fluctuating temperature and direct UV exposure. Parabolic solar drying was selected as an intensified solar method that can shorten drying time but requires higher initial investment. Hot-air tray drying served as a conventional controlled benchmark with stable temperature and airflow; however, it may promote thermal degradation of heat-sensitive compounds and relies on electricity. Finally, opaque greenhouse drying was included to protect UV-sensitive materials and reduce hygiene-related contamination (Kaveh et al., 2025). In addition, the hot-air exhaust and moisture-removal fans are powered by solar energy, eliminating the need for grid electricity and enabling a fully self-sustaining drying system.

Previous research on kratom has primarily focused on the analytical determination of alkaloid content in raw materials and commercial products (Citti et al., 2023; Todd et al., 2020; Sengnon et al., 2023), as well as on the pharmacological and toxicological properties of mitragynine (Meireles et al., 2019). Reported mitragynine contents range from 0.7 to 38.7% (w/w) in traditional and commercial products (Sharma & McCurdy, 2021) and from 0.31 to 4.94% (w/w) in kratom plants cultivated in Thailand, depending on seasonal and geographical conditions (Sengnon et al., 2023). Extraction studies have further confirmed mitragynine as the predominant alkaloid, with concentrations of 58.75, 35.87, and 3.85 mg g⁻¹ obtained from ethanol, methanol, and aqueous extracts, respectively (Limcharoen et al., 2022). In addition to alkaloids, kratom leaves contain considerable phenolic compounds and antioxidant activity, with reported total phenolic content of 252.92 mg GAE g⁻¹ (Limcharoen et al., 2022), while total phenolic content, total flavonoid content, and DPPH radical scavenging activity have also been reported as 90.88 mg GAE g⁻¹, 50.43 mg QE g⁻¹, and an IC₅₀ of 0.0397 mg mL⁻¹, respectively (Syed Azhar et al., 2023). However, although studies on other medicinal plants have demonstrated that drying method selection strongly influences phenolic retention and antioxidant capacity, systematic investigations linking drying methods to phenolic compounds, antioxidant activity, and mitragynine preservation in kratom leaves remain limited.

The present study addressed the lack of systematic evidence comparing color attributes, phenolic retention, and antioxidant preservation of kratom leaves under different drying technologies, with emphasis on an opaque solar-assisted greenhouse dryer with zero-energy airflow control. The objectives were to evaluate and compare four drying methods—direct sunlight drying, parabolic solar drying, hot-air tray drying, and the opaque greenhouse dryer with forced convection—in terms of physicochemical quality, total phenolic content, and antioxidant activity (DPPH and ABTS⁺ assays), and to identify the drying condition that provides the most favorable quality attributes for subsequent determination of mitragynine concentration. It was expected that solar-assisted low-temperature drying in the opaque greenhouse system would better preserve color, phenolic compounds, and antioxidant capacity than open sun drying while improving energy efficiency relative to hot-air tray drying.

2. Materials and methods

2.1 Materials and chemicals

Fresh kratom leaves (*Mitragyna speciosa* (Korth.) Havil.) were obtained from the Green Farmer Kalasin Community Enterprise, Non Buri Subdistrict, Sahatsakhan District, Kalasin Province, Thailand. All leaves were harvested at a similar maturity stage and transported to the laboratory within 6 h in insulated containers to minimize deterioration. Analytical-grade methanol, Folin–Ciocalteu reagent, sodium carbonate, 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), potassium persulfate, Trolox, and gallic acid standards. Mitragynine reference standard (purity \geq 98%).

2.2 Sample preparation

The harvested leaves, including fresh controls, were washed with clean water and soaked in 0.1% (w/w) potassium metabisulfite (KMS) solution for 15 min to reduce enzymatic browning and microbial contamination prior to analysis. After soaking, the leaves were drained and gently air-dried to remove surface moisture. The initial moisture content of fresh leaves was determined using a drying method at 105 °C to constant weight (AOAC, 2000) and expressed on a wet basis (% w.b.).

A completely randomized design was applied to compare four drying methods: (i) direct sunlight drying, (ii) parabolic solar drying, (iii) hot-air tray drying, and (iv) an opaque solar-assisted drying system modified from a greenhouse using a blackout plastic cover (opaque greenhouse drying). For each method, kratom leaves were dried in triplicates ($n=3$). In all treatments, the loading density was standardized at 0.625 kg m⁻² and leaf thickness single layer was maintained. Drying was continued until the final moisture content reached 10 \pm 2 % w.b. After drying, samples were packed in aluminum-laminated pouches, and stored at -18 °C until analysis.

2.3 Drying methods

2.3.1 Direct sunlight drying

Kratom leaves were spread in a single layer on stainless steel mesh trays and dried under direct sunlight from 8.00 A.M. to 5.00 P.M. Trays were positioned at 0.80 m. above ground. Ambient temperature, relative humidity and air velocity (Table 1) were recorded at 30 min intervals using a thermocouple (Testo 925, Germany) and hot-wire anemometer (AN510, Extech, USA). Simultaneously, solar radiation intensity was measured using a SOLAR meter (SM206-SOLAR, B'Angle, China). Leaves were turned every 2 h to promote uniform drying.

2.3.2 Parabolic solar drying

A parabolic solar dryer, based on the design proposed by Sudsuansee et al. (2023), was used, with samples prepared in the same manner as for direct sun drying. Kratom leaves were placed on perforated stainless steel trays inside the drying chamber. Drying temperature, relative humidity, and air velocity (Table 1) were recorded at 30 min intervals, and the drying process continued until the target moisture content was reached.

2.3.3 Hot-air tray drying

Hot-air tray drying (electric tray drying) was performed using a tray dryer (TD-10A, OFM, Thailand). Leaves were dried at 50 °C with an air velocity of 0.2 m s⁻¹ (Table 1). Samples were placed in a single layer on trays and rotated every 2 h to reduce spatial variability. Drying was terminated at the target moisture content.

2.3.4 Opaque greenhouse drying

An opaque solar-assisted drying system was developed by modifying a plant greenhouse structure into a drying chamber and applying a blackout filter (opaque covering) to eliminate direct solar radiation. The system was designed to promote solar-driven convective hot-air circulation and improve hygienic drying conditions. The blackout filter was installed on all greenhouse surfaces using a UV-stabilized blackout film (black-and-white panda film, Toyotani™, China) to prevent light penetration while retaining heat. Heated air was circulated through the chamber using a solar-powered fan, with airflow directed from beneath the solar panel to the drying chamber. Drying temperature, relative humidity and air velocity (Table 1) inside the chamber were recorded from 8:00 a.m. to 5:00 p.m. at multiple locations to assess spatial uniformity. Kratom leaves were dried on mesh trays at a loading density of 0.625 kg m⁻² until the target moisture content was reached.

Table 1. Drying conditions and operational parameters of different drying methods

Drying method	Drying temperature (°C)	Relative humidity (%)	Air velocity (m s ⁻¹)	Total drying time (h)	Heater power (W)
Direct sunlight	26.4–46.9	65.8–99.9 (Ambient)	0–1.3 (Natural airflow)	10	None
Parabolic solar	26.5–54.5	32.6–98.8	0–4.4 (Solar-driven airflow)	8	Solar energy
Hot-air tray	50.0±2.00	24.5–78.0	0.20±0.02	6	6 × 1000 W electric heaters
Opaque greenhouse	25.0–42.0	42.2–98.8	0–4.4 (Solar-driven airflow)	10	Solar energy

2.4 Chemical and physical properties analysis

2.4.1 Water activity measurement

Water activity (a_w) was measured by a water activity meter (Series 3TE, AquaLab, USA). Approximately 2.0 g of ground sample was placed in a container and placed in the water activity meter at 25°C.

2.4.2 Colorimetric analysis

Color values of fresh and dried kratom leaf samples were determined using a Colorimeter (UltraScan PRO, HunterLab, USA). The color parameters L* (lightness), a* (red–green), and b* (yellow–blue) were measured according to the CIELAB color system. Chroma (C*) and hue angle (°Hue) were subsequently calculated using Equations (1) and (2), respectively.

$$\text{Chroma } (c^*) = \sqrt{a^{*2} + b^{*2}} \dots\dots\dots(1)$$

$$\text{Hue angle } (^\circ\text{Hue}) = \tan^{-1} \frac{b^*}{a^*} \dots\dots\dots(2)$$

These values provide insight into the visual quality and color stability of the kratom leaves during the drying process.

2.4.3 Proximate analysis

Proximate composition was assessed according to AOAC. (2000) methods. Moisture content was measured via hot-air oven drying; crude protein was analyzed using the Kjeldahl method; crude fat was extracted with a Soxhlet apparatus; ash content was determined by incineration in a muffle furnace; and crude fiber was analyzed through acid-base digestion. Carbohydrate content was calculated by difference. All data were reported on a wet basis (% w.b.).

2.5 Determination of total phenolic content and antioxidant activity

2.5.1 Preparation of the extract

The powdered kratom leaf sample (0.1 g) was extracted with 9 mL of 95% (v/v) ethanol, sonicated at 25 °C for 15 min, and subsequently centrifuged to separate the supernatant. The clear extract was transferred to a light-protective container and stored at –20 °C until further analysis.

2.5.2 Determination of total phenolic content (TPC)

Total phenolic content (TPC) of dried kratom leaf extracts was determined using the Folin–Ciocalteu spectrophotometric method, as described by Singleton & Rossi (1965), with minor modifications. Gallic acid was used as a standard, and results were expressed as mg gallic acid equivalents per gram of extract (mg GAE g⁻¹). Standard gallic acid solutions were prepared in methanol at concentrations of 0.05, 0.075, 0.10, 0.125, 0.150, 0.175, and 0.20 mg mL⁻¹. Kratom leaf extracts were also prepared in methanol at concentrations of 0.1 and 1.0 mg mL⁻¹. An aliquot of 0.5 mL of each standard or sample solution was mixed with 2.5 mL of tenfold-diluted Folin–Ciocalteu reagent, followed by the addition of 2.0 mL of 7.5% (w/v) sodium carbonate solution. The reaction mixtures were incubated at room temperature for 30 min, and absorbance was measured at 760 nm using a UV–Vis spectrophotometer (UV-1800, Shimadzu, Japan). All determinations were performed in triplicate.

2.5.3 DPPH radical scavenging activity

DPPH radical scavenging activity was determined according to the method described by Brand-Williams et al. (1995) with minor modifications. A DPPH working solution (0.1 mM) was prepared in

95% ethanol. An aliquot of the extract (50 µL) was mixed with 2.0 mL of the DPPH solution and incubated in the dark at room temperature for 30 minutes. The absorbance was measured at 517 nm using a UV-Vis spectrophotometer. Trolox was used as the reference standard, and antioxidant activity was expressed as the percentage of inhibition was calculated using in equation (3):

$$\text{Inhibition (\%)} = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100 \quad \dots\dots\dots(3)$$

where A_{control} is the absorbance of the DPPH solution without extract and A_{sample} is the absorbance with extract.

2.5.4 ABTS⁺ radical cation decolorization assay

The ABTS⁺ radical scavenging assay was conducted according to the method described by Re et al. (1999) with minor modifications. The ABTS⁺ radical cation was generated by reacting ABTS solution (7 mM) with 2.45 mM potassium persulfate, followed by incubation in the dark at room temperature for 16 h. Prior to analysis, the ABTS⁺ solution was diluted with distilled water to obtain an absorbance of 0.70 ± 0.02 at 734 nm. An aliquot of the extract (50 µL) was mixed with the ABTS⁺ solution (3,000 µL) and incubated for 6 min at room temperature. Absorbance was then measured at 734 nm using a UV-Vis spectrophotometer. The percentage of radical scavenging activity was calculated using in equation (4):

$$\text{Radical Scavenging (\%)} = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100 \quad \dots\dots\dots(4)$$

Where A_{control} is the absorbance of the ABTS⁺ solution without extract and A_{sample} is the absorbance with extract.

The selection of dried kratom leaves was based on a comparative evaluation of four different drying methods. The selection criteria integrated physical properties, chemical properties, and antioxidant activities, the latter of which were determined using total phenolic contents, DPPH radical scavenging activity and ABTS radical cation decolorization assays. The drying treatment yielding the most favorable attributes was identified as the optimal method.

2.6 Determination of mitragynine concentration

Mitragynine analysis was performed using a method adapted from the experimental procedures described by Subtaeng et al. (2023) and Mudge & Brown (2017). Briefly, 0.200 g of powdered kratom leaf sample was weighed into a 15 mL centrifuge tube, extracted with 10 mL methanol, vortex-mixed for 30 s, and subjected to ultrasonic extraction at 60 °C for 30 min using an ultrasonic sonicator (LUC-405, LabTech, Korea). The extract was centrifuged at 7,000 rpm for 10 min (UNIVERSAL 320, Hettich, Germany), and the residue was re-extracted under identical conditions. The combined supernatants were filtered through a 0.22 µm PTFE membrane prior to analysis. Mitragynine quantification was carried out using HPLC-PDA (Waters 2998, Waters, USA) equipped with a C18 column (LiChrospher®, Merck, Germany; 4.6 mm × 250 mm, 5 µm). Chromatographic separation was performed under isocratic conditions using 20 mM ammonium

acetate buffer (pH 6.0) and acetonitrile (35:65, v/v) at a flow rate of 1.0 mL min⁻¹, with an injection volume of 5 µL and detection at 226 nm. The total run time was 15 min, and the retention time of mitragynine was approximately 11.28 min. Mitragynine content was calculated from the calibration curve and expressed as milligrams per gram of dry weight (mg g⁻¹).

2.7 Statistical analysis

The experiments were conducted using a Completely Randomized Design (CRD). All treatments and subsequent analyses were performed in triplicate (n=3) to ensure the reproducibility of the data. Experimental results are expressed as mean ± standard deviation (SD). Statistical significance was evaluated through One-way Analysis of Variance (ANOVA) to determine the differences between treatments. In cases where significant differences were detected, the comparison of means was performed using Duncan’s New Multiple Range Test (DMRT) at a confidence level of 95% (p ≤ 0.05). All statistical computations and data processing were executed using the SPSS software package, version 23.0 (IBM Corp., Armonk, NY, USA).

3. Result

3.1 Chemical and physical properties

3.1.1 Proximate composition

The proximate composition of dried kratom leaves differed significantly among drying methods (p ≤ 0.05), as shown in Table 2; however, fresh samples were not included in the statistical comparison because their initial moisture contents were not equivalent to those of the dried samples, which could lead to biased interpretation of compositional differences. Hot-air tray drying produced the lowest moisture content (8.66±0.64%), while direct sunlight drying showed the highest (10.36±0.49%). Fat content was highest in parabolic solar drying (4.09±0.09%), whereas protein content was the highest under direct sunlight (13.25±0.03%) and parabolic solar drying (13.35±0.08%). Hot-air tray drying was the highest ash content (5.71±0.09%). The opaque greenhouse drying was the highest carbohydrate content (56.43±0.65%).

Table 2. Proximate composition of fresh and dried kratom leaves

Approximately composition (%w.b.)	Fresh kratom leaves	Drying method			
		Direct sunlight	Parabolic solar	Hor-air tray	Opaque greenhouse
Moisture	56.33±0.30	10.36±0.49 ^a	9.07±0.85 ^b	8.66±0.64 ^b	9.19±0.39 ^b
Fat	2.05±0.04	3.58±0.11 ^b	4.09±0.09 ^a	4.01±0.09 ^a	3.46±0.04 ^b
Protein	18.35 ±0.12	13.25±0.03 ^a	13.35±0.08 ^a	12.59±0.18 ^b	12.07±0.04 ^c
Fiber	15.09±0.19	15.83±0.20 ^a	15.35±0.20 ^c	15.79±0.22 ^{ab}	15.57±0.10 ^{bc}
Ash	2.05±0.04	4.32±0.20 ^b	4.05±0.43 ^b	5.71±0.09 ^a	3.27±0.25 ^c
Carbohydrate	6.13±0.78	52.66±0.44 ^c	54.09±0.60 ^b	53.25±0.79 ^{bc}	56.43±0.65 ^a

Values are Means± Standard deviation.

Different superscript letters within a row indicate significant differences (p≤0.05).

3.1.2 Water activity

Water activity of kratom leaves was significantly affected by drying method ($p \leq 0.05$) (Table 3). The lowest water activity was observed in hot-air tray-dried samples ($a_w = 0.361 \pm 0.002$), followed by parabolic solar drying (0.381 ± 0.003), opaque greenhouse drying (0.417 ± 0.009), and direct sunlight drying (0.517 ± 0.006). All treatments achieved a_w values below 0.60, indicating conditions appropriate for the microbiological stability of dried herbal products.

Table 3. Water activity and color parameters of dried kratom leaves

Quality properties	Drying method			
	Direct sunlight	Parabolic solar	Hot-air tray	Opaque greenhouse
Water activity (a_w)	0.517±0.006 ^a	0.381±0.003 ^c	0.361±0.002 ^d	0.417±0.009 ^b
L*	52.08±1.18 ^b	50.03±0.36 ^c	46.63±0.86 ^d	54.36±0.54 ^a
a*	0.77±0.06 ^c	2.22±0.05 ^b	5.20±0.26 ^a	-1.65±0.15 ^d
b*	20.30±1.37 ^b	21.21±0.54 ^b	17.38±1.16 ^c	23.14±1.10 ^a
Chroma	20.32±1.37 ^b	21.32±0.54 ^b	18.14±1.18 ^c	23.20±1.11 ^a
°Hue	171.84±0.45 ^b	168.02±0.41 ^c	146.65±0.87 ^d	175.64±0.39 ^a

Values are Means±Standard deviation.

Different superscript letters within a row indicate significant differences ($p \leq 0.05$).

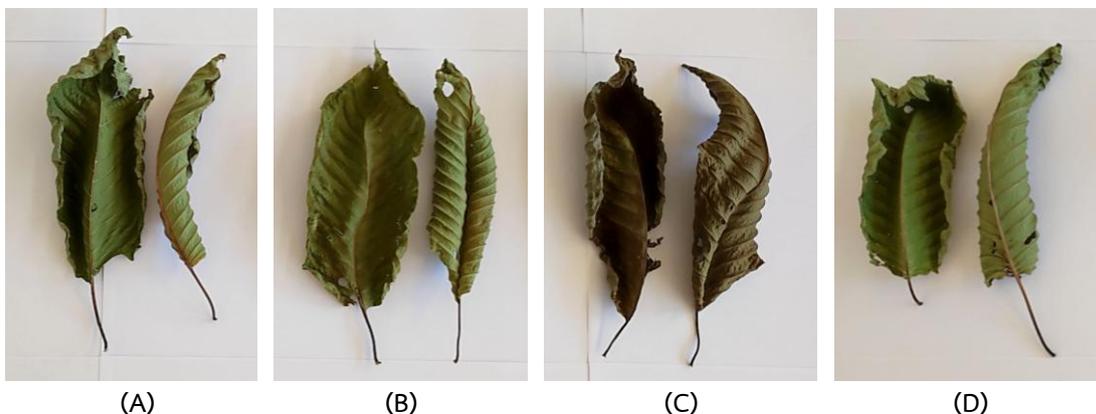


Figure 1. Visual appearance of dried kratom leaves obtained by different drying methods :
 (A) Direct sunlight (B) Parabolic solar (C) Hot-air tray (D) Opaque greenhouse

3.1.3 Color parameters

Significant differences were observed in all color parameters among the drying methods (Table 2). Opaque greenhouse drying yielded the highest lightness ($L^* = 54.36 \pm 0.54$), whereas hot-air tray drying produced the lowest L^* value (46.63 ± 0.86), indicating darker coloration. The a^* values revealed a pronounced shift toward redness in hot-air tray-dried samples (5.20 ± 0.26), while opaque greenhouse drying exhibited negative a^* values (-1.65 ± 0.15), indicating greater retention of green coloration.

Regarding yellowness (b^*) and chroma, opaque greenhouse–dried leaves showed the highest values ($b^* = 23.14 \pm 1.10$; chroma = 23.20 ± 1.11), whereas hot-air tray drying resulted in the lowest values ($b^* = 17.38 \pm 1.16$; chroma = 18.14 ± 1.18). Hue angle ($^\circ\text{Hue}$) also differed markedly among methods; opaque greenhouse drying presented the highest $^\circ\text{Hue}$ (175.64 ± 0.39), followed by direct sunlight (171.84 ± 0.45), parabolic solar (168.02 ± 0.41), and hot-air tray drying (146.65 ± 0.87). Visual appearance of dried kratom leaves obtained by different drying methods is shown in Figure 1.

3.2 Total phenolic content and antioxidant activity

The total phenolic content (TPC) and antioxidant activity of dried kratom leaves were significantly influenced by the drying method applied (Table 4). Among the evaluated techniques, the opaque greenhouse drying and direct sunlight drying exhibited the highest phenolic contents, with values of 196.64 ± 1.53 and 195.07 ± 1.23 mg GAE g^{-1} extract, respectively, and no statistically significant difference was observed between these two methods ($p \leq 0.05$). This result indicates that both drying approaches were effective in preserving phenolic compounds under relatively mild thermal conditions.

In contrast, kratom leaves dried using the hot-air tray dryer showed a markedly lower phenolic content (83.82 ± 0.91 mg GAE g^{-1} extract), suggesting substantial degradation of phenolic compounds due to elevated temperature and prolonged heat exposure. The parabolic solar dryer yielded intermediate phenolic values (185.88 ± 1.20 mg GAE g^{-1} extract), indicating partial preservation of phenolic compounds compared with the opaque greenhouse drying and direct sunlight drying methods.

Table 4. Phenolic content and antioxidant activity of dried kratom leaves

Drying method	Phenolic content (mg GAE/g extract)	DPPH radical scavenging activities (%inhibition)	ABTS ⁺ assays (%radical scavenging)
Direct sunlight	195.07 ± 1.23^a	73.37 ± 1.06^b	96.79 ± 1.84^b
Parabolic solar	185.88 ± 1.20^b	71.51 ± 0.93^b	94.27 ± 2.02^c
Hot-air tray	83.82 ± 0.91^c	66.77 ± 1.03^c	83.46 ± 1.72^d
Opaque greenhouse	196.64 ± 1.53^a	74.03 ± 0.82^a	97.14 ± 1.29^a

Values are Means±Standard deviation (S.D.).

Different superscript letters within a column indicate significant differences ($p \leq 0.05$).

Antioxidant activity, as determined by DPPH radical scavenging activity and ABTS⁺ radical cation decolorization assays, followed trends consistent with total phenolic content. The opaque greenhouse drying system exhibited the highest antioxidant activity, with DPPH inhibition of $74.03 \pm 0.82\%$ and ABTS⁺ radical scavenging of $97.14 \pm 1.29\%$, which were significantly higher than those observed for the other drying methods ($p \leq 0.05$). Direct sunlight drying showed comparable but slightly lower antioxidant activity ($73.37 \pm 1.06\%$ for DPPH and $96.79 \pm 1.84\%$ for ABTS⁺). Conversely, the hot-air tray drying resulted in the lowest antioxidant activity, with DPPH and ABTS⁺ inhibition values of $66.77 \pm 1.03\%$ and $83.46 \pm 1.72\%$, respectively.

Based on these results, opaque greenhouse drying with controlled hot-air circulation was identified as the most effective method for preserving color, total phenolic content, and antioxidant activity in dried kratom leaves. Consequently, this technique was selected as the optimal drying method for kratom leaves for subsequent determination of mitragynine content.

3.3 Mitragynine content of the fresh and dried kratom leaves

Mitragynine content was also strongly affected by the drying process. Fresh kratom leaves contained $6.54 \pm 15.03 \text{ mg g}^{-1}$, whereas leaves dried using the opaque greenhouse drying system as the most suitable drying method exhibited concentration of $9.83 \pm 14.68 \text{ mg g}^{-1}$.

4. Discussion

The present study demonstrated that the selection of drying method significantly influences the physicochemical quality of kratom leaves, particularly water activity and color attributes, which are critical indicators of product safety and consumer acceptance. All drying methods successfully reduced water activity to below 0.60, a threshold widely recognized as limiting microbial growth and enzymatic activity in dried plant materials (Prokopov & Tanchev, 2007).

Color preservation is another critical quality parameter for dried herbal products. The higher L^* values and lower a^* values observed in greenhouse-dried kratom leaves indicate reduced browning and improved retention of green pigments. This outcome aligns with the work of Maskan (2001) and Rubinskiene et al., (2015), reported that excessive thermal exposure and direct solar radiation accelerate chlorophyll degradation and non-enzymatic browning reactions. The use of a blackout filter in the opaque greenhouse drying system likely minimized photo-oxidative degradation, supporting earlier findings that shielding plant materials from ultraviolet radiation is essential for preserving visual quality in medicinal plants (Branisa et al., 2017).

Total phenolic content (TPC) and antioxidant activity are key indicators of the functional quality of kratom leaves. The present results showed that TPC and antioxidant activity of leaves dried in the opaque greenhouse system were comparable to those obtained by direct sunlight drying, as determined by both DPPH and ABTS⁺ assays. Although no significant difference in TPC was observed between these two methods, the opaque greenhouse system provided additional advantages, including more stable color attributes, lower water activity, and improved hygienic conditions due to protection from direct UV exposure and environmental contaminants. These combined quality factors support the selection of opaque greenhouse drying over direct sunlight drying, consistent with previous studies reporting that low-temperature, UV-shielded drying environments are effective in preserving phenolic compounds and antioxidant capacity while enhancing overall product quality (Arslan & Özcan, 2011; Puranik et al., 2012).

In contrast, hot-air tray drying resulted in a marked reduction in TPC and antioxidant activity, which can be attributed to the higher and constant drying temperature (50 °C for 6 h) compared with the milder conditions of the solar-based methods (opaque greenhouse 25–42 °C for 10 h; direct sunlight 26.4–46.9 °C for 10 h; parabolic solar 26.5–54.5 °C for 8 h). Prolonged exposure to elevated temperature is known to

accelerate thermal degradation, oxidation, and polymerization of phenolic compounds, leading to decreased radical scavenging capacity (Vega-Gálvez et al., 2009; Deng et al., 2019). Similar temperature-dependent losses have been reported in red pepper, oregano, and *Andrographis paniculata*, where drying above 45–50 °C significantly reduced TPC and antioxidant activity (Vega-Gálvez et al., 2009; Soiklom et al., 2024).

Additionally, antioxidant activity assessed via DPPH and ABTS⁺ assays were better preserved in kratom leaves processed with the opaque greenhouse drying system operated at lower and fluctuating temperatures with UV shielding (25–42 °C). These results are consistent with previous findings that drying systems with moderate thermal load and protection from ultraviolet radiation help maintain the integrity of polyphenolic and flavonoid compounds in medicinal plants (Ng et al., 2020; Rajurkar & Hande, 2011).

The mitragynine content obtained in the present study, expressed on a dry weight basis (mg g^{-1}), was consistent with the range reported by Leksungnoen et al. (2022), who found concentrations in Thai-grown kratom leaves varying from 7.5 to 26.6 mg g^{-1} . In this experiment, fresh kratom leaves contained $6.54 \pm 0.15 \text{ mg g}^{-1}$, while leaves dried using the opaque greenhouse system—the selected optimal method—exhibited a concentration of $9.83 \pm 0.14 \text{ mg g}^{-1}$. The differences between studies may be attributed to several factors, including variations in cultivar and genetic background, geographical and seasonal growing conditions, leaf maturity, and analytical procedures such as extraction efficiency and chromatographic protocols.

5. Conclusion and suggestions

5.1 Conclusion

This study evaluated the effects of different drying techniques on the chemical and physical properties, total phenolic content, and antioxidant activity retention of kratom leaves. All drying methods successfully reduced moisture content and water activity to levels suitable for safe storage. However, notable differences were observed, with the opaque greenhouse drying system exhibiting the most favorable color characteristics and antioxidant activity. Although the total phenolic content was comparable to that obtained by direct sunlight drying, the opaque greenhouse method provided superior hygienic attributes. In contrast, hot-air tray drying resulted in greater reductions in phenolic content and antioxidant capacity, likely due to thermal degradation. Mitragynine was quantified only in samples from the selected optimal drying condition; therefore, comparative conclusions regarding mitragynine preservation among drying methods cannot be drawn, and this represents a limitation of the present study. From a practical perspective, opaque greenhouse drying achieved target moisture and water activity levels appropriate for commercial storage while operating with minimal external energy input. These findings support the application of solar-assisted, low-temperature greenhouse drying as a feasible approach for community-scale kratom processing in Thailand, consistent with requirements for product quality, hygiene, and energy sustainability.

5.2 Suggestions for future research

5.2.1 Drying Kinetics and Compound Degradation Modeling

Further research is recommended to develop comprehensive drying kinetic and degradation models for kratom leaves, particularly for phenolic compounds and mitragynine, using a thin layer drying model. In addition, the establishment of such models would support process optimization and provide predictive tools for preserving product quality during drying.

5.2.2 Scale-Up and Techno-Economic Evaluation

Subsequent studies should evaluate the scalability, energy efficiency, and economic feasibility of the modified greenhouse drying system at pilot and industrial scales. Moreover, techno-economic assessment should incorporate key indicators such as payback period, energy consumption per kilogram of dried product, greenhouse dryer capacity, and operational and maintenance costs. Furthermore, life-cycle and cost-benefit analyses would facilitate the adoption of this technology for sustainable community and commercial kratom processing.

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