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Novel Microwave-Assisted Drying Technique for Thai Medicinal Herbs Utilizing an Asymmetrical Double-Feed Microwave/Vacuum System

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Abstract

This study explored the drying efficiency of various medicinal herbs – Fa Talai Jone, Gotu Kola, Pueraria Krua, Turmeric, Plai and Black Galingale – employing different methods, such as a low-power microwave system with asymmetric biphasic waves coupled with a vacuum at power settings of 800 W and 1,600 W, and traditional hot-air oven and freeze-drying techniques. The investigation assessed the effect of different drying approaches on herb quality for batches of 1,000 g and 2,000 g, noting the temperatures used: 80 °C for hot air and 60 °C for microwaves at 1,600 W. Findings demonstrated that microwave drying, especially when integrated with a vacuum system, outperformed hot-air oven drying in terms of efficiency, achieving faster moisture reduction without compromising herb volume or moisture content. In contrast, hot air-drying exposed herbs to greater temperatures, resulting in significant colour changes and texture degradation, whereas freeze-drying preserved the herbs' original volume, colour and texture intact. The study further examined how vacuum pressure and microwave energy contributed to moisture elimination, underscoring microwave technology's ability to rapidly reduce moisture content and efficiently generate heat. Additionally, post-drying analyses of microbial, yeast and mould levels varied across the drying methods, indicating that microwave and vacuum drying technologies could significantly enhance the preservation and drying power of medicinal herbs, making them preferable for processing in the pharmaceutical and herbal industries.

Keywords: Microwave-assisted drying; Thai medicinal herbs; Fa Talai Jone; Gotu Kola; Pueraria Krua; Turmeric; Plai; Black Galingale.
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1. Introduction

Incorporating the integration of highly sought-after herbs such as Gotu Kola, Pueraria Kruea, Turmeric, Plai and Black Galingale into various downstream industries is anticipated to increase the market value from approximately 18.2 billion baht in 2019 to an estimated 20 billion baht by 2020. This projection is consistent with the younger generation's growing preference for natural herbal treatments over traditional medicines, a trend that is being actively supported by targeted government policies, notably the herbal development master plan for 2017-2021. These initiatives are poised to enhance the integration of these herbs into the National List of Essential Medicines and their utilisation across diverse sectors such as cosmetics, dietary supplements and pharmaceuticals, underpinning their pivotal role in holistic health maintenance strategies.

Addressing the crucial phase of drying these herbs requires overcoming the challenges associated with slow drying rates and minimal heat conduction, which impede efficient moisture removal. The adoption of microwave-drying techniques pioneered in the 1940s and subsequently refined across food and chemical engineering domains utilises the principle of internal energy absorption within a hybrid microwave field, characterised by its 3-dimensional mixed-wave nature.[1–4] This approach has proven effective in enhancing drying uniformity and speed, as evidenced by the unity of theoretical and experimental findings in the literature.[5–8]

This research focuses on optimising microwave-drying methodologies, which underscores the significance of

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variables such as material placement within the heating zone and its intrinsic properties, as well as the strategic distribution of electromagnetic fields, in maximising energy absorption and, consequently, drying efficiency.[9–12] Notably, integrating vacuum systems with microwave-drying techniques has emerged as a promising advancement, offering notable improvements in preserving the colour and nutritional integrity of dried products, thereby surpassing traditional drying methods.[13–15] Despite historical challenges such as safety concerns and technological constraints, current research endeavours focus on refining microwave- and vacuum-drying processes through a comprehensive, transdisciplinary approach. This approach encompasses electromagnetic theory, material science, and advanced numerical modelling to identify optimal operational parameters, such as magnetron power, pressure, and temperature settings, to achieve superior drying outcomes. Such concerted efforts highlight the transformational potential of microwave-drying technologies in revolutionising the processing landscape for herbs and similar materials, ensuring the preservation and enhancement of their intrinsic health benefits for end-user consumption.[16–20]

2. Materials and methods

This study encompasses two principal experimental approaches: asymmetric microwave drying, incorporating vacuum assistance and traditional hot-air drying. The objective is to explain differences in moisture evaporation rates, resultant colouration and overall morphological characteristics of medicinal herbs, as detailed in Table 1.

2.1 Materials

The herbs utilized in the study were collected from a farm located in the northern region of Thailand and were preserved at a temperature of 10 °C until preparation for experimentation. Before the drying process, the majority of the tea leaves were equilibrated to ambient air temperature for a duration of 3 hours. The samples' initial moisture content assessments indicated a value of 172% on a dry basis (d.b.). As illustrated in Fig. 1, the drying time applied was consistent across herbs derived from the same batch.

2.2 Methods

2.2.1 Unsymmetrical double-feed asymmetric microwave

As shown in Fig. 2, this study employed a commercial drying system leveraging microwave technology. It featured dual feed vacuum systems operating at a frequency of 2,450 MHz and microwave powers set to 800 W and 1,600 W for single and asymmetric dual feed magnetrons, respectively, to dry 1,000 g and 2,000 g of herbs. The system's drum rotated at a

(a) Paniculata *(Andrographis paniculata (Burm. f.) Wall. ex Nees.)*

(b) Gotu Kola *(Centella asiatica (L.))*

(c) Pueraria mirifica *(Pueraria candollei Graham ex Benth. var mirifica)*

(d) Turmeric *(Curcuma longa (L.))*

(e) Zingiber Cassumunar (*Zingiber montanum* (*J. Koenig*) *Link ex A. Dietr.*)

(f) Black Galingale (*Kaempferia parviflora Wallich. ex Baker.*)

Fig. 1 (a) Paniculata (Andrographis paniculata (Burm. f.) Wall. ex Nees.), (b) Gotu Kola (Centella asiatica (L.)), (c) Pueraria mirifica (Pueraria candollei Graham ex Benth. var mirifica), (d) Turmeric (Curcuma longa (L.)), (e) Zingiber Cassumunar (Zingiber montanum (J. Koenig) Link ex A. Dietr.)) and (f) Black Galingale (Kaempferia parviflora Wallich. ex Baker.).

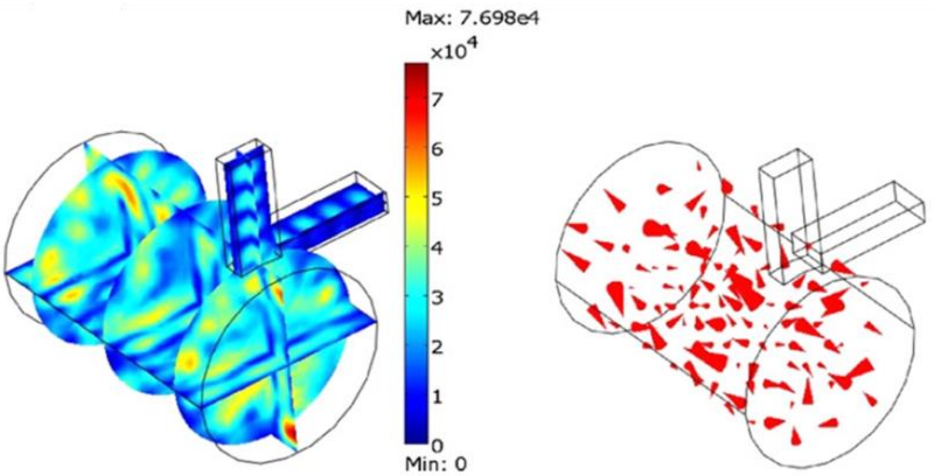


Fig. 2 The commercialised device uses a combined unsymmetrical double-feed asymmetric microwave with low energy and a vacuum system.

Table 1. Conditions and characteristics of dried Thai medicinal herbs.

Hot-air drying		Microwave drying	
Parameter	Value	Parameter	Value
		Power	800 and 1600 W
Maximum temperature for drying	80 °C	Maximum temperature for drying	80 °C
Duration	80 min	Duration	80 min
Moisture	% Dry basis	Moisture	% Dry basis
Colour	Lightness (L*), redness (a*) and yellowness (b*)	Colour	Lightness (L*), redness (a*) and yellowness (b*)
Nutritional and physical properties	Bioactive substances and minerals	Nutritional and physical properties	Bioactive substances and minerals
Microorganism	Total plate count and yeast and moulds	Microorganism	Total plate count and yeast and moulds

rate of 10 revolutions/min under vacuum pressures of 385 and 535 Torr, allowing for operation in both continuous and pulse modes.

2.2.2 Testing

Utilizing laboratory-scale apparatus with a precision of 0.01 g, moisture content (on a d.b.) and dry matter content were quantified in accordance with the protocols sanctioned by the Association of Official Analytical Collaboration (see Fig. S1). To ascertain the mean temperature of the bulk load within the drying cavity, an optical fibre thermometer (LUXTRON Fluroptic Thermometer Model 790, with an accuracy of ± 0.5 °C) was employed. This methodology circumvents the use of conventional thermocouples, which are susceptible to microwave energy absorption, leading to spurious temperature measurements. Instead, optical fibres, which do not interfere with microwave fields, were utilized to ensure accurate temperature monitoring. The temperature within the cavity was regulated using an infrared camera. Moreover, a Multimeter TM Series Digital Meter, interfaced with a computer, was deployed for process feedback control and to monitor cavity temperatures. The samples' surface temperatures were precisely measured using an infrared camera, achieving an accuracy of ± 0.5 °C.

This investigation employs a multi-faceted approach to evaluate sample characteristics and changes. Initially, to quantify moisture reduction, samples are weighed at consistent 10-minute (min) intervals, facilitating the calculation of moisture loss and subsequent determination of residual moisture levels. Additionally, the SELON LC100 high-performance liquid chromatography system is utilized to analyse physicochemical attributes, such as colour, bioactive substances and mineral content, as well as microbiological properties. Moreover, colour appearance assessments are made using the WF30-16 colorimeter, which is adept at analysing a wide range of dried herb samples. It incorporates advanced, imported components and is designed for both precision and stability, ensuring simplicity in operation and learning. The colorimeter is cost-effective for colour analysis, especially proficient in evaluating textured materials, surfaces with pitting or samples that are coarse or large in granular size. The design and functionality of the WF30 precision colorimeter are aligned with the standards established by the International Commission on Illumination (CIE), ensuring its applicability and reliability in color measurement tasks.

3. Results and discussion

3.1 Moisture and temperature

3.1.1 Paniculata (Andrographis paniculata (Burm. f.) Wall. ex Nees.)

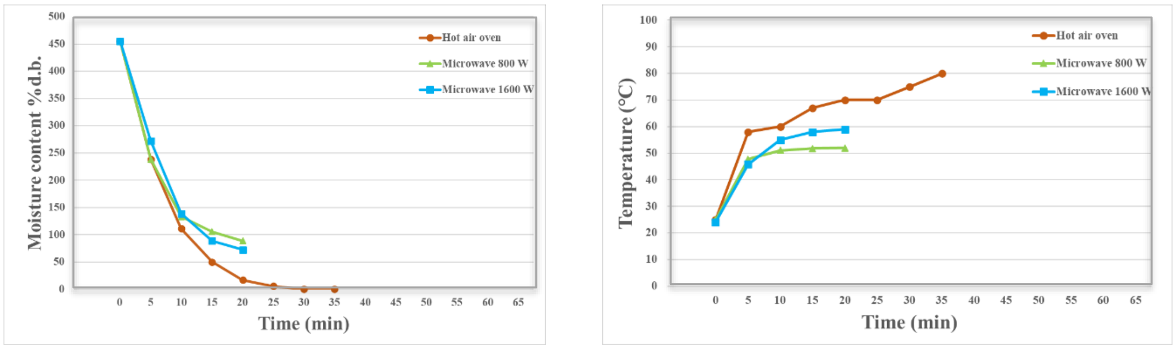
The impact of temperature and duration on the moisture content of Paniculata is quantitatively analysed using two drying methodologies, as depicted in Fig. 3. Hot-air oven drying and microwave drying at power levels of 800 W and 1,600 W, respectively. The initial analysis of drying kinetics, using a 1,000 g sample of *Andrographis paniculata*, reveals a pronounced decline in moisture content, with the steepest decrease observed between moisture levels of 450% and 100%. The comparative analysis indicates no significant difference in the drying efficiency (as represented by the slope of the moisture reduction curve) between the two microwave power settings and hot-air oven drying during the initial phase. However, a significant reduction in the slope is observed in the subsequent phase, suggesting a deceleration in moisture loss as the sample approaches a dehydrated state.

Interestingly, after 15 min of drying, samples subjected to hot-air oven drying exhibited a higher percentage of moisture loss compared to those dried using microwave methods. This can be attributed to the heat transfer mechanism; air conduction effectively heats the narrow, leaf-like surface area of Paniculata, enhancing moisture evaporation more efficiently than microwave irradiation. It is noted that the hot-air oven achieves higher temperatures compared to the microwave oven, with a rapid increase in temperature observed within the first 0–5 min of drying, followed by a plateau after 10 min. In addition, extending to a 2,000-g sample reveals similar drying kinetics, with a noticeable adjustment in the timing of drying phases to accommodate the increased mass: the initial rapid drying phase extends from 0 to 15 min, followed by a slower drying period from 20 to 40 min. In both sample masses (1,000 g and 2,000 g), hot-air oven drying proved more effective in reducing moisture content than microwave drying despite similar temperature profiles.

This observation underscores the principle that the augmentation of microwave power results in a more effective conversion of electromagnetic energy into thermal energy, thereby accelerating moisture evaporation. Despite this, the inherent characteristics of hot-air drying, particularly its capacity for higher temperature achievement and effective heat distribution across the plant material, render it more productive in moisture removal over extended periods. This elucidates the crucial role of drying technology and methodology in optimising the dehydration process of herbal materials, where the choice of technique significantly influences the rate and efficiency of moisture loss.

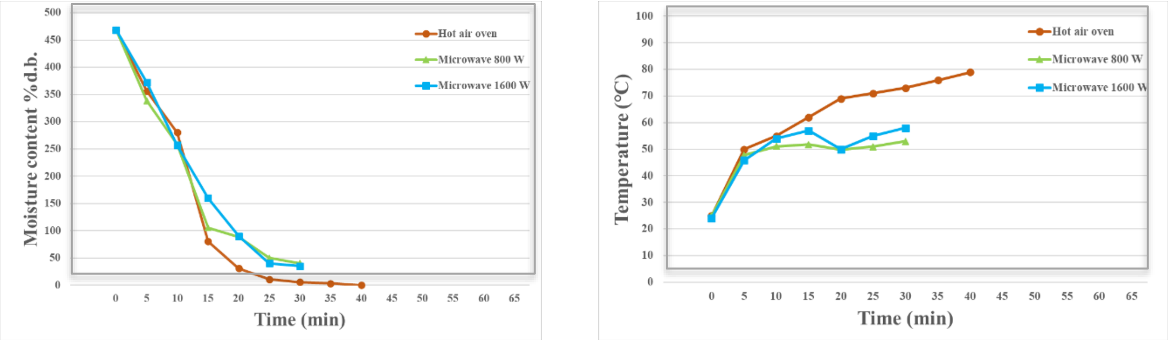
3.1.2 Gotu Kola (*Centella asiatica* (*L.*))

The effect of temperature and duration on the moisture content of Gotu Kola is critically examined in Fig. 4, highlighting the drying kinetics under various conditions. The analysis



(a) 1,000 g subjected to 800 W

(b) 1,000 g subjected to 1,600 W



(c) 2,000 g subjected to 800 W

(d) 2,000 g subjected to 1,600 W

Fig. 3 Moisture content ((a) and (c) subjected to 800 W) and temperatures ((b) and (d) subjected to 1600 W) at different drying times of Paniculata (*Andrographis paniculata (Burm. f.) Wall. ex Nees.*).

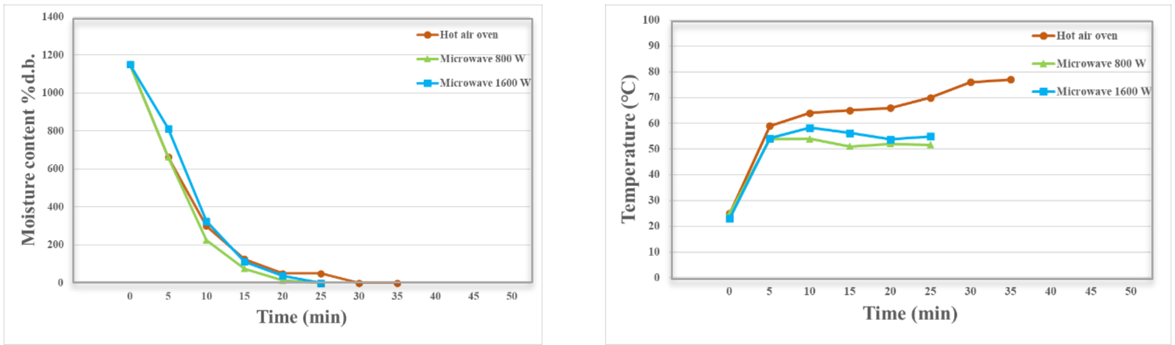
encompasses microwave drying at power settings of 800 W and 1,600 W and conventional hot-air oven drying with sample masses of 1,000 g and 2,000 g.

During the initial phase of 0-15 min, a rapid decrease in moisture content is observed for both drying methods and sample sizes, with moisture levels dropping from 1,200% to 100%. This phase is characterised by a steep graph slope, indicating a significant rate of moisture loss. However, the rate of drying, as depicted by the slope of the graph, diminishes in the subsequent period despite maintaining power levels in microwave drying and constant conditions in the hot-air oven. This suggests a deceleration in moisture evaporation as the sample approaches a stabilised moisture content of approximately 100%. For up to 35 min of drying, there is no discernible difference in the efficiency of moisture removal between the hot-air oven and microwave drying methods. It is noteworthy that the temperature dynamics within the microwave oven show a rapid increase within the initial 0–5 min, followed by a more gradual rise post-10 min of drying, irrespective of the power setting. Both 800 W and 1,600 W microwave settings exhibit similar thermal behaviours, whereas the hot-air oven consistently achieves higher temperatures than its microwave counterparts. Furthermore, extending to a 2,000-g sample of Gotu Kola reveals that the drying curve exhibits similar two-phase kinetics as observed with the 1,000-g samples. The initial rapid drying phase is extended to 0-20 min, followed by a slower 25-45 min drying period. This alteration in the drying curve indicates a proportional increase in drying time with sample mass, maintaining a comparable rate of moisture loss to that observed with hot-air oven drying. Furthermore, the initial 0-10 min temperature profile for hot-air oven drying mirrors was observed in the microwave process, suggesting a parity in temperature elevation between the two drying methods. However, after 15 min, the hot-air oven sustains higher temperatures than the microwave drying process, corroborating its enhanced thermal capacity. Thus, microwave and hot-air oven drying influence the moisture content of Gotu Kola through a dynamic interplay of temperature and time. The initial rapid moisture loss phase is followed by a period of reduced drying efficiency, with hot-air ovens demonstrating a superior capacity for achieving higher temperatures and, potentially, a more consistent drying outcome over extended periods. This comparison underscores the critical consideration of drying methodology in optimising the dehydration process for herbal materials, highlighting the nuanced differences in thermal behaviour and efficiency between microwave and conventional hot air-drying techniques.

3.1.3 Pueraria mirifica (*Pueraria candollei Graham ex Benth. var mirifica*)

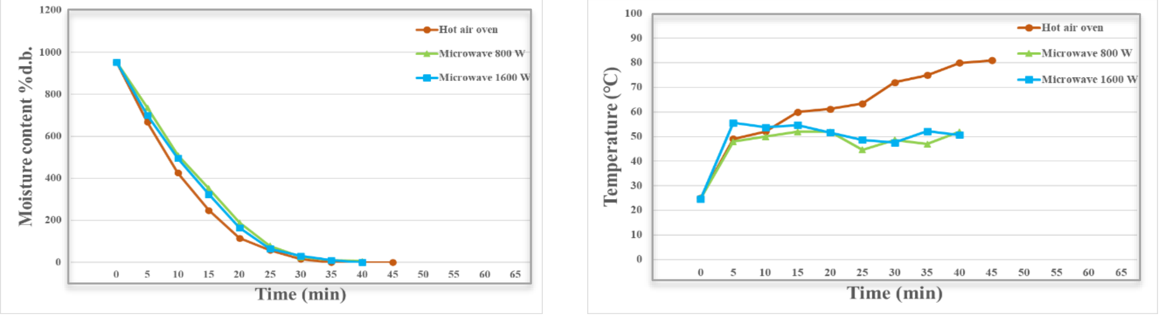
Figure 5 presents the effect of temperature and time on the moisture content of Pueraria Mirifica, employing microwave drying at power levels of 800 W and 1,600 W and conventional hot-air oven drying with sample masses of 1,000 g and 2,000 g.

For Pueraria Mirifica weighing 1,000 g, the analysis reveals a rapid moisture reduction from 900% to 30% moisture content within a 0 to 35-min timeframe, indicating no significant difference in the dehumidification rate between the two microwave power settings. It was observed that the



(a) 1,000 g subjected to 800 W

(b) 1,000 g subjected to 1,600 W



(c) 2,000 g subjected to 800 W

(d) 2,000 g subjected to 1,600 W

Fig. 4 Moisture content ((a) and (c) subjected to 800 W) and temperatures ((b) and (d) subjected to 1,600 W) at different drying times of Gotu Kola (*Centella asiatica* (*L.*))

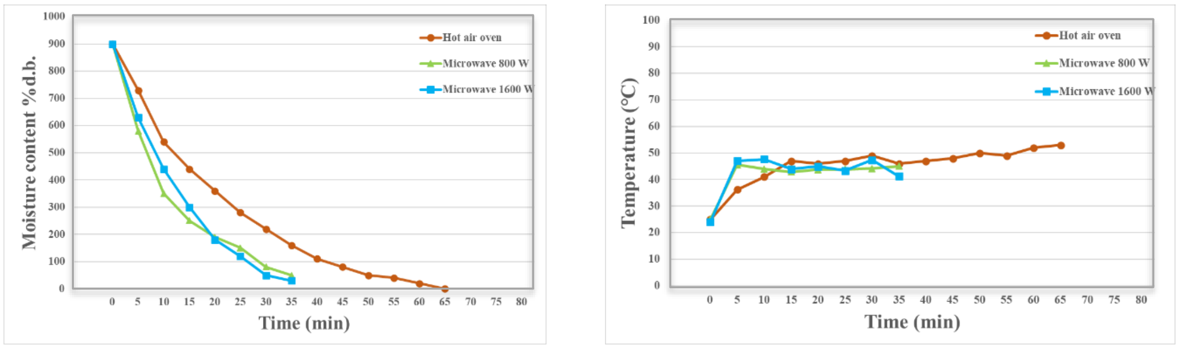
rate of moisture loss in the microwave drying process is greater than that in hot-air oven drying, with the microwave process requiring 65 min to achieve the targeted moisture level. In contrast, the hot-air oven demonstrated a superior ability to reach higher temperatures more rapidly within the initial 0-5 min of drying, with a constant increase in temperature observed after 10 min. The most rapid temperature increases in hot-air oven drying occurred within the first 0-15 min, after which the temperature plateaued.

For samples weighing 2,000 g, the drying process was characterised by distinct phases, beginning with a rapid temperature rise in the initial 0-5 min, suggesting microwaves heat faster than hot-air ovens. The subsequent phase continued with a steady temperature increase. Notably, the duration required for drying bigger samples (2,000 g) extended to approximately 50 min for both microwave and hot-air oven methods, indicating a longer process than the 1,000-g samples, with hot-air oven drying requiring more time overall. Thus, both temperature and time significantly impact the moisture content of *A. paniculata* and Pueraria Mirifica, with microwave drying offering a more aggressive moisture reduction rate compared to hot-air oven drying. However, the hot-air oven excels in rapidly achieving higher temperatures, especially during the initial drying stages. The efficiency and duration of the drying process are influenced by the method employed and the sample's mass, highlighting the complexity of optimising drying parameters for herbal materials. The segmented phases of temperature increase and stabilisation during drying underscore the nuanced control required to maximise dehumidification efficiency while preserving the quality of the dried products.

3.1.4 Turmeric (*Curcuma longa (L.)*)

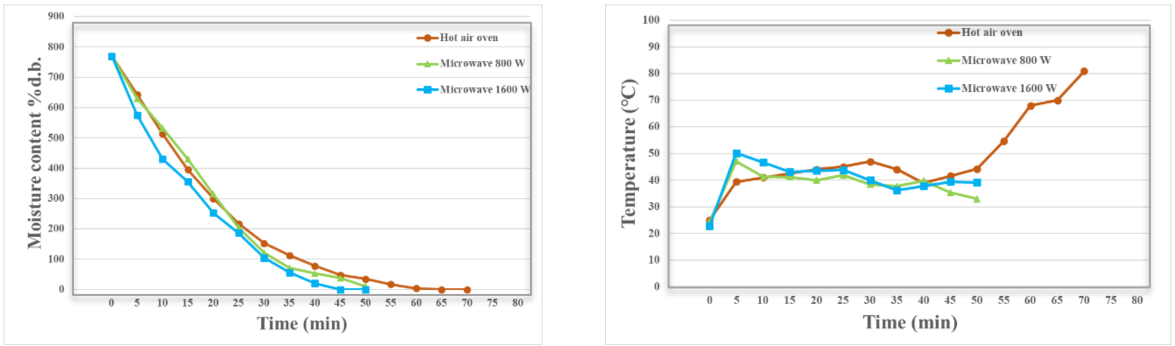
Figure 6 presents an analysis of the moisture reduction in turmeric (*Curcuma longa*), processed through microwave drying at power levels of 800 W and 1,600 W and conventional hot-air oven drying for sample masses of 1,000 g and 2,000 g. The observed moisture content of turmeric decreased dramatically from approximately 280% to 50% in the initial phase of drying. Throughout this phase, no significant variance in the moisture reduction rate (indicated by the graph's slope) was observed between the different power settings in microwave drying or when compared to hot-air oven drying. However, beyond 20 min of drying time, a notable deceleration in moisture loss was recorded, as evidenced by a reduced slope in the graph, eventually leading the moisture content towards zero. The comparative analysis of drying methods found that the hot-air oven resulted in a lower final moisture content than microwave drying during the initial period of up to 10 min, indicating a rapid temperature increase. Subsequently, in the second phase (after 15 min), the efficiency of moisture removal by the hot-air oven surpassed that of microwave drying. Both microwave settings, 800 W and 1,600 W, demonstrated consistent temperature increases throughout the drying process.

For turmeric samples weighing 2,000 g, the drying behaviour exhibited a biphasic pattern similar to the smaller samples but with reduced efficiency in moisture removal



(a) 1,000 g subjected to 800 W

(b) 1,000 g subjected to 1,600 W



(c) 2,000 g subjected to 800 W

(d) 2,000 g subjected to 1,600 W

Fig. 5 Moisture content ((a) and (c) subjected to 800 W) and temperatures ((b) and (d) subjected to 1,600 W) at different drying times of Pueraria mirifica (*Pueraria candollei Graham ex Benth. var mirifica*).

for both drying methods as the drying duration extended beyond that required for 1,000 g samples. Notably, at the 800-W power setting, microwave drying was less effective in reducing moisture content than at 1,600 W, with the hot-air oven and drying temperatures being lower at the 1,600-W setting. Despite this, microwave drying at both 800 W and 1,600 W achieved a consistent temperature increase after the initial 10 min, surpassing the temperature capabilities of hot-air ovens.

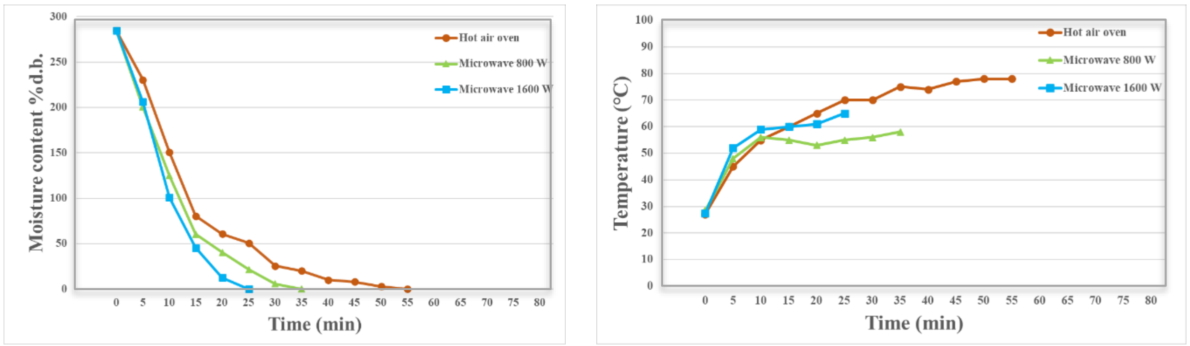
Accordingly, both microwave and hot-air oven drying impact turmeric's moisture content significantly, with each method exhibiting distinct phases of moisture reduction efficiency. The initial rapid decrease in moisture content is followed by a more gradual phase of moisture removal. Compared to microwave drying, the hot-air oven demonstrates a more robust capability for temperature elevation and sustained drying efficiency over time, especially in the latter stages of drying. This distinction underscores the importance of selecting appropriate drying technologies and adjusting parameters to optimise the dehydration process for herbal materials, considering both the initial rapid drying phase and the subsequent slower drying phase to achieve desired moisture levels.

3.1.5 Zingiber Cassumunar (*Zingiber montanum* (*J. Koenig) Link ex A.Dietr.*))

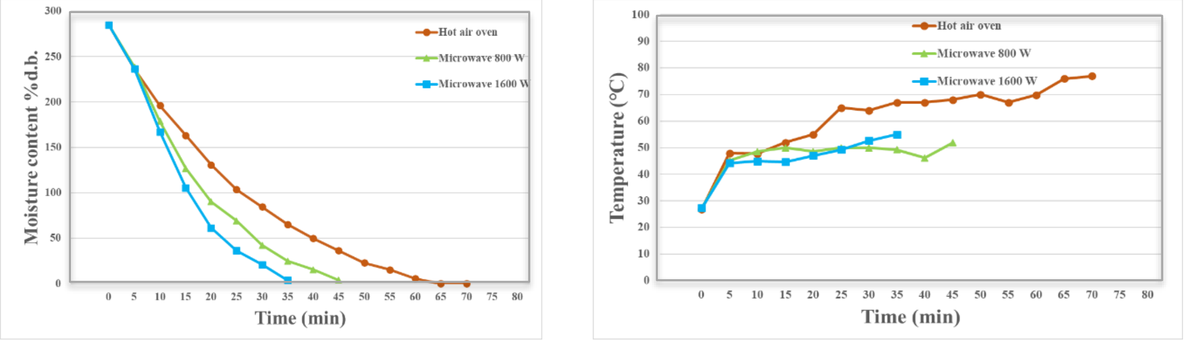
Figure 7 illustrates the relationship between moisture content and drying parameters (temperature and time) for Zingiber cassumunar, focusing on the efficacy of moisture removal over time using both microwave drying at power settings of 800 W and 1,600 W and conventional hot-air oven drying, with initial sample masses of 1,000 g and 2,000 g.

For the 1,000-g samples, a swift reduction in moisture content was noted, plummeting from approximately 250% to 50% d.b. During this process, the rate of moisture loss (indicated by the graph's slope) did not exhibit any discernible difference between the microwave power settings or when compared to the hot-air oven drying within the initial phase. However, a decline in the slope was observed after 15 min, indicating a reduction in the rate of moisture loss. Interestingly, both drying methods achieved similar final dry moisture contents, although a hot-air oven required a longer duration to reach the same level of dryness compared to microwave drying. The temperature escalation within the first 0–5 min was rapid for both microwave settings, with a consistent increase observed thereafter.

Employing 2,000-g samples revealed a biphasic drying curve similar to that of the 1,000-g samples, with consistent characteristics but different final moisture percentages. The rate of temperature increase during drying was more rapid than that observed for the 1,000-g samples, highlighting the mass's influence on the drying kinetics. This detailed examination demonstrates that both microwave and hot-air oven drying can effectively reduce the moisture content of Zingiber cassumunar, although the efficiency and rate of drying vary according to the method and conditions applied. Although microwave drying offers a quicker reduction in moisture content, hot-air ovens achieve higher temperatures, potentially offering a more thorough drying process over a longer period. The analysis underscores the importance of considering both

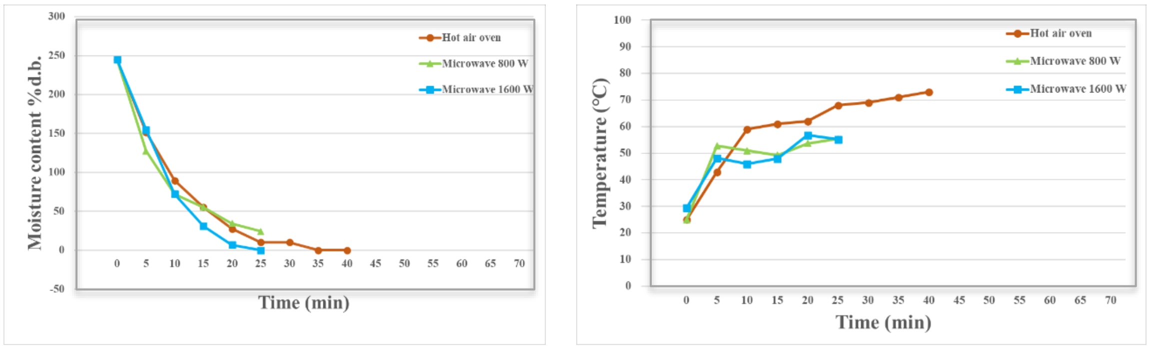


(a) 1,000 g subjected to 800 W (b) 1,000 g subjected to 1,600 W

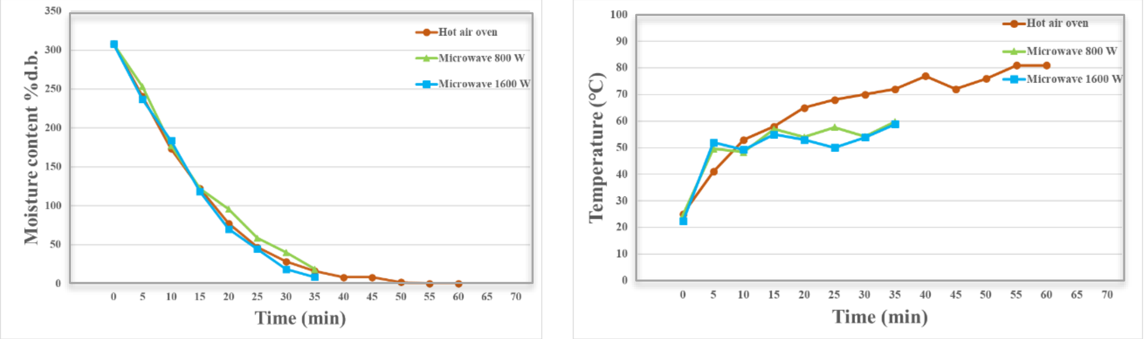


(c) 2,000 g subjected to 800 W (d) 2,000 g subjected to 1,600 W

Fig. 6 Moisture content ((a) and (c) subjected to 800 W) and temperatures ((b) and (d) subjected to 1,600 W) at different drying times of Turmeric (*Curcuma longa* (*L.*)).



(a) 1,000 g subjected to 800 W (b) 1,000 g subjected to 1,600 W



(c) 2,000 g subjected to 800 W (d) 2,000 g subjected to 1,600 W

Fig. 7 Moisture content ((a) and (c) subjected to 800 W) and temperatures ((b) and (d) subjected to 1,600 W) at different drying times of Zingiber Cassumunar (*Zingiber montanum (J. Koenig) Link ex A. Dietr.*).

the initial rapid drying phase and the subsequent slower drying period to optimise drying strategies for herbal materials, taking into account the specific requirements of different sample masses for effective moisture removal.

3.1.6 Black Galingale (*Kaempferia parviflora Wallich. ex Baker.*)

Figure 8 systematically presents the relationship between temperature, time and the moisture content reduction in Black Galingale for samples of 1,000 g and 2,000 g. The analysis revealed that for a 1,000-g sample, the moisture content sharply declined from 140% to 20%, with microwave drying at 800 W and 1,600 W showing no significant difference in the rate of moisture reduction, as indicated by a consistent slope. Contrarily, the hot-air oven facilitated a slower moisture reduction compared to microwave drying, with a slight decrease in the rate of drying noted after 20 min of processing. In this context, the efficiency of microwave drying was evidently higher than that of hot-air oven drying.

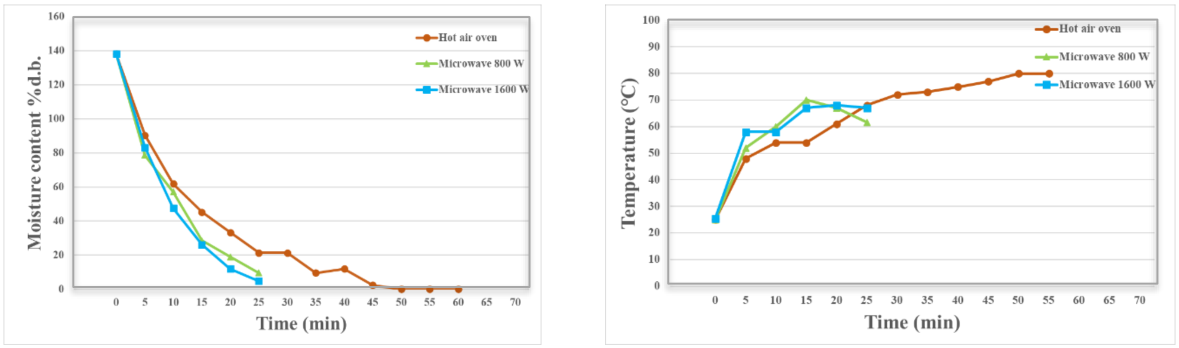
The initial phase of drying, occurring within the first 0-5 min, witnessed the most rapid temperature increase, highlighting a more time-consuming drying process. Despite the power settings, both 800 W and 1,600 W maintained a uniform rate of temperature rise after the first 10 min. Interestingly, the hot-air ovens operated at cooler temperatures compared to the microwaves, with the temperature in the ovens reaching 80 °C at the 55-minute mark.

The drying behaviour of a 2,000-g sample of Black Galingale mirrored the characteristics observed with the 1,000-g samples, albeit with differences in the percentage of moisture lost. This analysis suggests that the drying efficiency for larger masses was less pronounced for both hot-air oven and microwave drying methods. Notably, drying a 1,000-g sample in the hot-air oven took longer than microwave drying at 800 W and 1,600 W. The maximum temperature increases during the first 0-5 min were consistent across both drying methods, with microwave drying at both power settings maintaining a steady temperature rise beyond 10 min. The temperature increase was comparable between hot-air oven and microwave drying methods, indicating a similar thermal behaviour across these drying technologies.

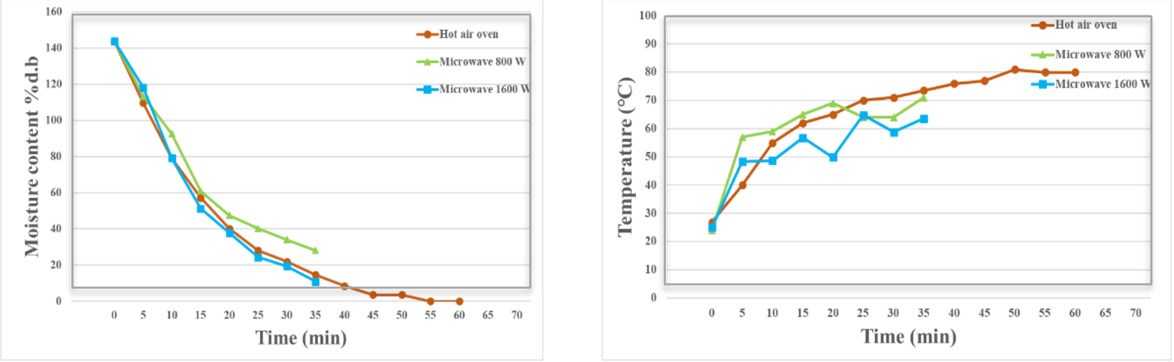
It can be seen that the complex interplay between the drying method, sample mass, and thermal dynamics is involved in reducing moisture content in Black Galingale. Microwave drying showcases a higher efficiency and rapid temperature increase, which translates to quicker moisture content reduction. However, the comparative thermal performance between microwave and hot-air oven drying emphasises the need to tailor the drying process to the specific requirements of the herb being dried, considering factors such as the desired rate of moisture removal, energy consumption and the temperature sensitivity of the material.

3.2 Physical appearances

The morphological changes observed in six herbal specimens - Fah Talai Jone, Gotu Kola, Pueraria Krua, Turmeric, Plai and Black Galingale – subjected to microwave drying at power levels of 800 W and 1,600 W. Post-drying analysis revealed a



(a) 1,000 g subjected to 800 W (b) 1,000 g subjected to 1,600 W



(c) 2,000 g subjected to 800 W (d) 2,000 g subjected to 1,600 W

Fig. 8 Moisture content ((a) and (c) subjected to 800 W) and temperatures ((b) and (d) subjected to 1,600 W) at different drying times of Black Galingale (*Kaempferia parviflora Wallich. ex Baker*).

universal reduction in volume or size across the majority of the herbs, indicative of significant moisture loss during the drying process. Exceptionally, Black Galingale maintained its original dimensions, distinguishing it from the other specimens in terms of its physical response to drying (Table S1).

The comparative analysis further extends to the impact of drying these herbs in a conventional hot-air oven, observing analogous reductions in volume or size, affirming that the primary mechanism of size reduction is moisture evaporation regardless of the drying technique employed. A notable alteration in colour was observed, suggesting chemical or physical changes within the herbs that may affect their visual appeal. The surface texture of the herbs became rough and desiccated, a direct consequence of the dehydration process. Despite these physical transformations, the aromatic properties of the herbs were largely preserved, maintaining their distinctive odours.

Similar remarks were made for the herbs subjected to hot-air drying at 80 °C for 80 min, where a decrease in volume or size was uniformly noted, attributed to the effective removal of moisture. This process also resulted in a rough and dry surface texture and a change in colour from their original states, underscoring the impact of drying conditions on the physical characteristics of herbal materials. This analysis underlines the intricate relationship between drying technology, power settings and the resultant physical properties of herbal specimens. It highlights the essential balance required to achieve optimal drying outcomes – preserving the functional and sensory attributes of the herbs while effectively reducing moisture content.

3.3 Colour

Figure 9 describes the alterations in colour attributes of various herbs – Fa Talai Jone (*Andrographis paniculata*), Gotu Kola (*Centella asiatica*), Pueraria (*Pueraria mirifica*), Turmeric (*Curcuma longa* (*L.*)), Plai (*Zingiber cassumunar*) and Black Galingale (*Kaempferia parviflora Wallich. ex Baker.*) – utilising the CIELAB (L*a*b*) colour space, defined by the International Commission on Illumination. This colour space quantitatively describes the colour as having three values: L* for lightness, a* for the green-red spectrum and b* for the blue-yellow spectrum.

For Fah Talai Jone, initial lightness was measured at 36.12, slightly decreasing post-drying to 34.73, indicating minimal impact on brightness from microwave drying. The a* value, representing the green-red spectrum, changed from −4.71 (indicating a green tendency) pre-drying to −1.72 and −3.06 after drying with hot air and microwaves, respectively, showcasing a slight shift towards less green. The b* value, reflecting the blue-yellow spectrum, remained relatively stable, suggesting a minimal change in the yellow hue post-drying.

Gotu Kola exhibited an initial yellow hue (b* value) of 43.67, which remained relatively consistent post-drying, registering at 45.85 and 46.96 for hot-air and microwave drying, respectively. The red-green spectrum (a* value) shifted from a significant green presence (−10.55) towards neutrality (0) after drying, indicating a noticeable reduction in greenness.

Pueraria Mirifica showcased notable lightness (L*) pre- and post-drying, with values starting at 77.72 and decreasing to 62.54 after microwave drying, indicating a reduction in brightness and a shift towards dullness. The red (a*) and yellow (b*) values observed minor adjustments, suggesting slight changes in hue towards less vivid colours post-drying. Plai experienced an increase in lightness post-drying, with initial L* values at 62.61 rising after both hot-air and microwave drying, indicating an enhancement in brightness. This increase was paralleled by changes in the a* and b* values, suggesting red and yellow hues post-drying alterations. Turmeric showed that the initial lightness (L* value) was recorded at 39.55, which experienced a slight reduction to 31.03 following the drying processes. This modest decrease suggests that microwave drying exerts a minimal effect on the overall brightness of Turmeric. In addition, the chromaticity coordinates, the a* value, which quantifies the colour on a green to red spectrum, shifted from an initial −5.66, indicating a lean towards green, to −2.33 and −4.11 after undergoing hot-air and microwave drying, respectively. This transition reflects a subtle shift towards a less green appearance, hinting at a minor alteration in the red-green balance of Turmeric's colour due to the drying methods. Furthermore, the b* value, indicative of the blue-yellow spectrum, exhibited remarkable stability throughout the drying process.

Black Galingale initially recorded a lightness (L*) of 34.56, which slightly increased to 37.06 post-hot-air oven drying, with further enhancement post-microwave drying. Both red (a*) and yellow (b*) hues exhibited minimal changes post-drying, indicating stable colour preservation across drying methods.

Although microwave and hot-air drying methods generally maintain or slightly modify the colour characteristics of herbs, specific changes in lightness, redness, and yellowness depend on the herb type and the drying method applied. This highlights the importance of considering the effects of drying techniques on the visual and possibly phytochemical qualities of herbs, which could influence their applicability in various industries, including food, pharmaceuticals and cosmetics.

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3.4 Nutritional and physical properties: Bioactive substances and minerals

Figure 10 presents the impact of different drying methods, including hot-air frying and microwave drying, on the content of bioactive compounds and minerals in various medicinal herbs. It can be revealed that there was a notable decrease in the concentration of bioactive compounds following the application of heat-based drying techniques, with the lowest levels of these vital chemicals observed post-hot-air frying. In contrast, freeze-drying was identified as the most effective method for preserving the highest concentrations of bioactive compounds, outperforming microwave drying, which yielded moderate levels. This discrepancy in compound preservation is attributed to the thermal degradation associated with the heat produced during the drying processes, which adversely affects the stability and integrity of bioactive chemicals. Additionally, the analysis highlighted a reduction in the levels of various minerals, including vitamin C, lithium ion (Li^+), sodium ion (Na^+), ammonia ion ($NH4^+$), potassium ion (K^+), calcium ion (Ca^{2+}) and magnesium ion (Mg^{2+}), across all six herbs subjected to drying. This decline is directly correlated with the thermal exposure during the drying process, which affects the bioavailability and preservation of these essential nutrients.

It is critical to select appropriate drying methods to optimise the retention of bioactive compounds and essential minerals in medicinal herbs. The findings advocate for freeze-drying as a superior technique for preserving the phytochemical profile and nutritional value of herbs, thereby ensuring that their therapeutic efficacy and dietary benefits are maintained post-processing. However, the decrease in the amounts of bioactive components after drying processes

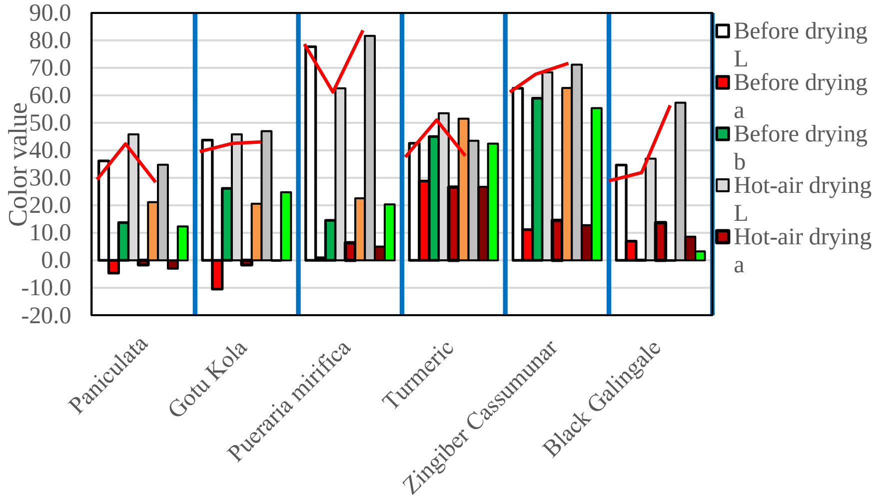
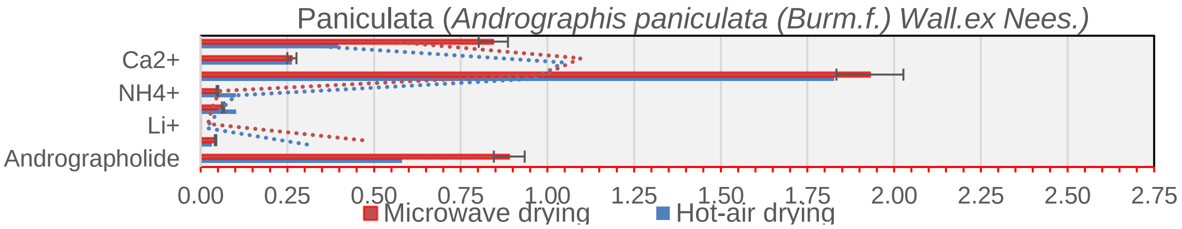
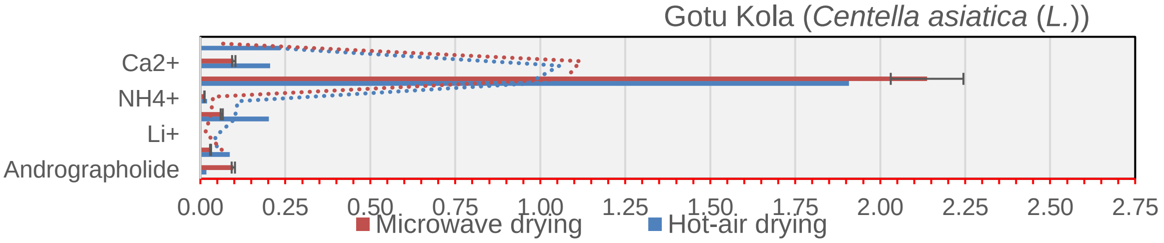


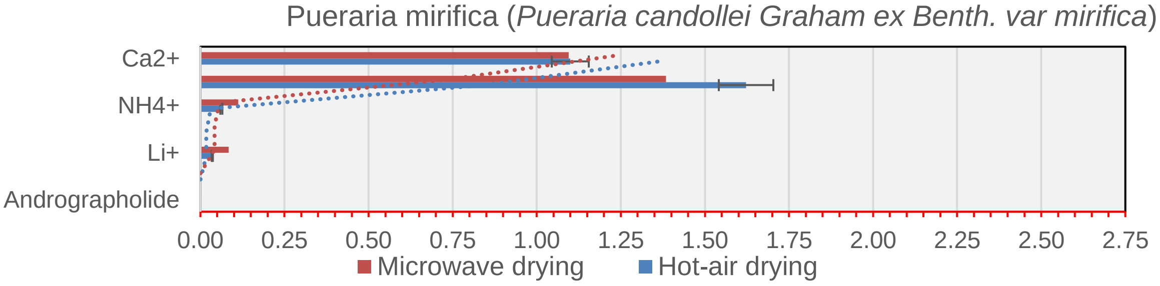
Fig. 9 Colour values of herbs before and after hot-air microwave drying ((L* represents lightness, a* represents redness and b* represents yellowness))



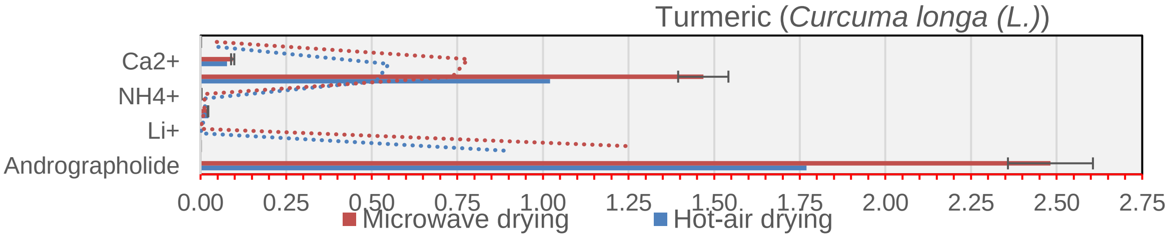
(a) Paniculata (*Andrographis paniculata* (*Burm. f.) Wall.ex Nees.*)



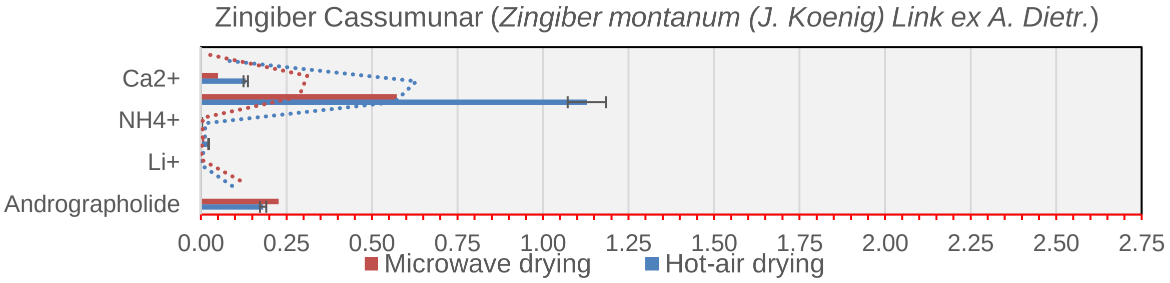
(b) Gotu Kola (*Centella asiatica* (*L.*))



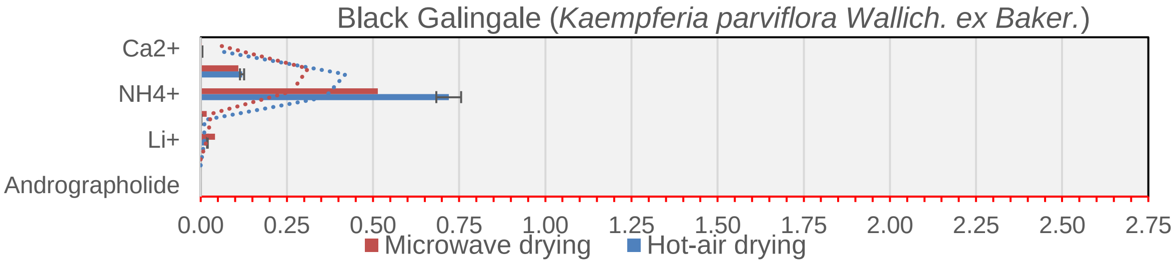
(c) Pueraria mirifica (*Pueraria candollei Graham ex Benth. var mirifica*)



(d) Turmeric (*Curcuma longa* (*L.*))



(e) Zingiber Cassumunar (*Zingiber montanum* (*J. Koenig*) *Link ex A. Dietr.*)



(f) Black Galingale (*Kaempferia parviflora Wallich. ex Baker.*)

Fig. 10 Bioactive substances and minerals.

particularly those involving heat, such as hot-air frying and microwave drying, is primarily attributed to the phenomenon of thermal degradation. This degradation directly impacts the stability and concentration of sensitive bioactive compounds and essential minerals within medicinal herbs, reducing their therapeutic efficacy and nutritional value. Moreover, during heat-based drying processes, the elevated temperatures can break down chemical bonds within bioactive molecules, resulting in the alteration or loss of these compounds. This is evident in the study that reported the lowest retention of vital chemicals in medicinal herbs, such as Andrographolide, Asiaticoside and Curcuminoids, following hot-air frying. The intense heat not only diminishes the concentration of these compounds but also affects the levels of critical minerals (vitamin C, Li^+, Na^+, $NH4^+$, K^+, Ca^{2+} and Mg^{2+}). The thermal exposure encountered during these drying methods alters the chemical state or solubility of these minerals, thereby reducing their bioavailability.

In contrast, freeze-drying stands out for its ability to preserve bioactive compounds in medicinal herbs by minimising thermal exposure through sublimation under vacuum, thus maintaining the herbs' structural integrity and ensuring optimal retention of phytochemical and nutritional values. This method contrasts sharply with heat-intensive drying techniques, which lead to thermal degradation, adversely affecting the concentration and integrity of essential bioactive components and minerals. Furthermore, emerging techniques such as atmospheric cold plasma pre-treatment combined with osmotic dehydration offer promising enhancements in bioactive component retention, highlighting the importance of selecting drying methods that effectively preserve the medicinal and nutritional properties of herbs.[21]

3.5 Microorganism

The microbiological quality of dried herbs, including Andrographis paniculata, Pueraria, Plai and Black Galingale, was subjected to different drying methods: hot-air, microwave and, for some, convection oven drying. The objective was to assess the efficacy of these drying processes in eliminating bacteria, yeasts and moulds and to ascertain compliance with community product standards for microbial content. For Andrographis paniculata, despite eliminating bacteria following hot-air and microwave drying, the dried herb failed to meet the community product standards. The standards stipulate that the total colony-forming unit (CFU) of microbes per gram must not exceed 5×10^5, and the CFU for yeast and mould must be under 100. Although bacterial levels were within acceptable limits, the CFU counts for yeast and mould did not satisfy the specified requirements, indicating a microbial quality concern.

Conversely, Pueraria samples dried using both convection oven and microwave methods successfully met all microbial quality requirements. The drying processes effectively controlled microbial growth, including yeasts and moulds, ensuring compliance with the prescribed standards.

Table 2. Microorganisms are total plate count and yeast and moulds after different drying methods.

Herbs	Microorganism (CFU/g)	Hot-air drying	Microwave drying
Paniculata (*Andrographis paniculata (Burm. f.) Wall. ex Nees*.)	Total plate count	4.2×10^6	3.6×10^6
	Yeast and moulds	2.9×10^3	1.9×10^4
Gotu Kola (*Centella asiatica* (*L.*))	Total plate count	6.4×10^4	2.0×10^5
	Yeast and moulds	1.5×10^3	6.3×10^1
Pueraria mirifica (*Pueraria candollei Graham ex Benth. var mirifica*)	Total plate count	1.2×10^3	4.2×10^3
	Yeast and moulds	1.3×10^2	5.9×10^2
Turmeric (*Curcuma longa* (*L.*))	Total plate count	4.3×10^4	1.4×10^5
	Yeast and moulds	2.7×10^2	2.5×10^2
Zingiber cassumunar (*Zingiber montanum* (*J. Koenig*) *Link ex A. Dietr*.)	Total plate count	3.8×10^5	4.8×10^4
	Yeast and moulds	7.7×10^1	8.3×10^1
Black Galingale (*Kaempferia parviflora Wallich. ex Baker*.)	Total plate count	3.4×10^4	7.1×10^5
	Yeast and moulds	3.9×10^2	7.6×10^2

For Plai, the drying methods employed were able to reduce the microbial presence to acceptable levels, with all microorganisms meeting the specified criteria. However, the documentation notes that yeast and mould were detected following drying in both hot-air ovens and microwaves, suggesting a potential misunderstanding in the original text or a discrepancy in microbial quality outcomes. Black Galingale demonstrated complete compliance with microbial standards across all three drying methods. Post-drying analyses confirmed that bacteria and fungi (yeasts and moulds) were within acceptable limits, satisfying the community product standards. Therefore, the microbial quality assessment of dried herbs reveals the varying efficacy of different drying methods in ensuring microbiological safety. Although most drying methods proved effective in reducing microbial content to meet or exceed community standards, challenges in controlling yeast and mould levels in specific samples highlight the importance of optimising drying conditions and selecting appropriate methods based on the particular microbial resilience of each herb, as indicated in Table 2.

3.6 Energy consumption

The energy consumption detailed in Table 3 presents a

Table 3. Energy consumption for hot-air drying and microwave drying.

Drying method	Electrical equipment	Watt (W)	On-off Factor	Working hour (h)	Total Watt-hour (Wh)		Weight (g)	Energy consumption kWh/kg	Percentage compared to hot-air oven
Hot-air	Heater	450	0.8	1.3	468		1,000	0.468	–
							2,000	0.234	–
Microwave	Microwave	800	0.8	0.3	192	342	1,000	0.468	26.92 ↓ (Decreased)
	Vacuum pump	500	1.0	0.3	150		2,000	0.234	26.92 ↓ (Decreased)
	Microwave	1,600	0.4	0.3	192	342	1,000	0.342	26.92 ↓ (Decreased)
	Vacuum pump	500	1.0	0.3	150		2,000	0.171	26.92 ↓ (Decreased)

comparative analysis of energy consumption between a vacuum microwave system and a conventional hot-air oven during herb drying. This analysis reveals the efficiency and energy usage associated with each method under specific operational conditions.

For the hot-air oven, with each operation consuming 450 W of power, a utilisation factor of 0.8 and a drying duration of 80 min (1.3 h), the calculation yields a total energy consumption of 468 Wh. Applying this to dry 1,000 g of herbs results in an energy index of 0.468 Wh/g. When the drying process involves 2,000 g of herbs, the energy index effectively halves to 0.234 Wh/g due to doubling the herb mass without increasing the total energy consumption.

The operational parameters differ in the scenario of vacuum microwave drying at power settings of 800 W and 1,600 W. For the 800 W setting, with a factor of 0.8, combined with a vacuum pump operating at 500 W with a factor of 1.0 and a drying time of 0.3 h, as well as the 1,600-W setting with a factor of 1.0 and a drying time of 0.4 h (24 min), the total energy consumption is calculated to be 342 Wh. This results in an energy index of 0.432 Wh/g for drying 1,000 g of herbs and 0.171 Wh/g for drying 2,000 g, reflecting increased energy efficiency with larger quantities of herbs. Using a vacuum microwave system for drying 1,000 g and 2,000 g of herbs yields an energy savings of approximately 26.92% compared to a conventional hot-air oven. This significant reduction in energy consumption demonstrates the vacuum microwave's superiority in energy efficiency for drying processes, offering a more sustainable option for large-scale herb drying operations. The findings advocate for implementing vacuum microwave drying as a more energy-efficient alternative to traditional hot-air ovens, aligning with sustainable practices and reducing operational costs in herb-drying processes.

3.7 Discussion

The decrease in drying time with an increase in microwave power is observed across various studies, including those examining the drying of herbs and nectarine slices. This effect can be attributed to the fundamental principles of microwave heating and its interaction with the material being dried. This study focused on herbs such as Black Galingale, Turmeric, Gotu Kola, Pueraria Krua, Plai, and Fa Talai Jone. The employment of a low-power microwave system, augmented by asymmetric biphasic waves and a vacuum system operating at 800 W and 1,600 W, markedly improved the drying process. This method, when compared to traditional hot-air oven drying and freeze-drying, not only reduced the drying time but also preserved a higher moisture content within the herbs, which is crucial for retaining their therapeutic properties. The rapid temperature increases within the initial 5 min of microwave drying highlight the efficiency of microwave energy in penetrating the material and uniformly heating the water content for evaporation.

Similarly, in the study examining the drying of nectarine slices using hybrid hot air–microwave drying methods at various microwave power levels (80-320 W), the Midilli–Kucuk model indicated that the hybrid method significantly reduced drying time while maintaining or enhancing product quality.[22] This method achieved more effective moisture diffusivity and a minor total colour difference (ΔE) than hot-air drying alone. The increase in microwave power levels corresponded with a decrease in drying time and a modification in product parameters, such as colour, surface roughness and microstructural changes, indicating a delicate balance between drying efficiency and product quality preservation.

The decrease in drying time with increased microwave power in both studies is primarily due to the direct interaction of microwave energy with the water molecules within the material. Microwave heating is more efficient than conventional heating because it generates heat internally within the material, resulting in faster and more uniform moisture evaporation. The increased power translates to a higher intensity of microwave energy available to interact with water molecules, thus accelerating the drying process. Moreover, using a vacuum in conjunction with microwave drying, as seen in the herbal drying study, further enhances drying efficiency by reducing the air pressure surrounding the material. This lowers the boiling point of water, allowing moisture to evaporate at lower temperatures and thus reducing the risk of thermal degradation of heat-sensitive compounds. The decrease in drying time with the increase in microwave power can be attributed to the efficient internal heating mechanism of microwave energy and enhanced evaporation rates under vacuum conditions. This principle applies universally across different materials, including herbs and nectarine slices, demonstrating the broad applicability of microwave-assisted drying techniques in improving drying efficiency while preserving or enhancing the quality of the dried product.

4. Conclusion

The study demonstrated that the drying of herbs such as Fa Talai Jone, Gotu Kola, Pueraria Krua, Turmeric, Plai and Black Galingale was significantly improved by using a low-power microwave system featuring asymmetric biphasic waves, combined with a vacuum system at power settings of 800 W and 1,600 W. This advancement was validated through comparative analyses against traditional hot-air oven drying and freeze-drying, under varying herb quantities, showcasing its efficacy in a commercial context. It was observed that, for both 1,000 g and 2,000 g samples, drying with a hot-air oven resulted in a significant reduction in moisture content. However, this method was outperformed by microwave drying, which not only reduced drying time but also preserved a higher moisture content, which is beneficial for retaining certain herbal properties. The overall temperature achieved by hot-air ovens was higher, yet microwave drying demonstrated a more rapid temperature increase within the initial 5 min, indicating its efficiency.

Drying resulted in a reduction of volume and an alteration in texture, with herbs becoming dry and rough to the touch. This effect was particularly pronounced with hot-air oven drying, compared to microwave or freeze-drying. Freeze-drying uniquely preserved the herbs' volume, colour and odour, suggesting its superiority in maintaining the physical and sensory properties of herbs. Utilising vacuum pressure in conjunction with microwave energy proved effective in further reducing the moisture content of herbs, highlighting the role of energy input in enhancing drying efficiency. This method facilitated controlled dehydration while maintaining the integrity of bioactive compounds and essential minerals within the herbs. In addition, the study found variances in microbial load after drying, with hot-air oven drying achieving the lowest levels of microorganisms, yeast and mould. Conversely, microwave and freeze-drying maintained medium to high microbial levels. The investigation also found a correlation between herb surface area and moisture loss rate, suggesting that larger surface areas facilitate more efficient drying.

The findings highlight the importance of selecting appropriate drying technologies based on specific herbal properties and desired end-product quality. Microwave-assisted vacuum drying emerges as a highly efficient method, offering significant advantages over traditional drying methods in energy efficiency, herbal quality preservation and microbial safety, making it a preferable choice for the pharmaceutical and herbal industries.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

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