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Integrated Ultrasound-Assisted Convective–Microwave Drying for the Dehydration of Medicinal Plants

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ABSTRACT

Ultrasound-assisted convective-microwave drying (UACMD) is an emerging hybrid drying method that combines hot-air convection, microwave heating and ultrasound cavitation to enhance moisture transfer and preserve bioactive compounds in medicinal herbs. This review summarizes its advantages, including a 30-80% reduction in drying time, improved energy efficiency, and better retention of antioxidants, essential oils, and color. However, challenges, such as thermal degradation and scale-up complexity remain. Future developments emphasize the integration of smart controls (artificial intelligence, computer vision, and hyperspectral imaging) and the tailoring of protocols for specific herb types, positioning UACMD as a sustainable and high-performance solution for modern herbal drying.

Introduction

The ultrasound-assisted convective microwave drying (UACMD) has emerged as a promising technique for medicinal plant processing, meeting the increasing demand for high-quality and sustainable herbal products (Nurhaslina et al., 2022; Zhang et al., 2021). Conventional drying methods such as hot-air drying (HAD) often lead to long processing time, loss of essential oils and volatiles, and color degradation (Zhao et al., 2020; Tepe and Tepe, 2024). In response, advanced technologies, including microwave, vacuum, freeze and ultrasound-assisted drying-have been developed to improve drying performance (Ghanbarian et al., 2020; Hassoun et al., 2024).

Among the emerging hybrid methods, the ultrasound-assisted convective–microwave drying (UACMD) has attracted particular attention due to its integration of hot-air convection, microwave heating, and ultrasound-enhanced mass transfer. This combination enables more efficient moisture removal and shows potential for better preservation of bioactive compounds such as antioxidants and volatile aromas, while maintaining product structure (Żbik et al., 2023). Current studies report improvements in effective moisture diffusivity, protection of heat-sensitive compounds like polyphenols and vitamins, and enhancements in texture, porosity, and rehydration. From the energy perspective, the UACMD has been associated with lower specific energy requirements compared to hot-air drying, although optimization is still required to address challenges such as uneven heating and preprocessing demands. These aspects provide the foundation for this review which summarizes available findings and outlines the perspectives for future.

Principal Drying Technologies.

Conventional hot-air drying is simple and low-cost but often leads to long drying times and poor bioactive retention. Microwave and ultrasound-assisted techniques improve speed and efficiency yet may pose a risk of thermal degradation or structural damage if not optimized. Combining them in the UACMD offers a balanced approach that enhances drying performance while preserving sensitive compounds and product quality.

Convective Drying

Convective drying remains a widely adopted method in food and herbal processing due to its balance of efficiency, cost, and product quality. It operates via heated airflow that induces surface evaporation and internal moisture diffusion-reflecting coupled heat and mass transfer driven by temperature gradients and vapor pressure differences. A drying rate is influenced by air temperature, velocity, and material thickness, with higher temperatures and airflow enhancing evaporation, while greater thickness slows diffusion (Ghanbarian et al., 2020; Szadzińska and Mierzwa, 2021). The process is often modeled using the convective heat transfer coefficient (h_t) and mass transfer coefficient (h_m), which quantify energy and moisture exchange (Szadzińska and Mierzwa, 2021). Optimization of these parameters is essential to improve the drying kinetics and maintain product integrity.

Convective drying remains one of the most widely utilized and economically viable drying methods across various sectors, notably in food and herbal processing (Bhattacharya et al., 2015; Yoon, 2024). Its straightforward design, typically involving a blower, drying chamber, and heating unit, facilitates ease of maintenance and scalability for both small-scale and industrial operations (Casaverde-Pacherrez et al., 2022). The modular setup allows for capacity expansion with minimal structural modifications (Yoon, 2024). Thermally, convective drying ensures stable and uniform heat distribution, reducing risks of structural deformation and enhancing the process consistency (Szadzińska and Mierzwa, 2021; Inla et al., 2023). Under optimal conditions, typically at 50-70°C with airflow velocities of 1.0-3.0 $m \cdot s^{-1}$, the method achieves high drying efficiency while preserving the product integrity (Ghanbarian et al., 2020). Moreover, it can be hybridized with complementary Bhattacharya technologies such as microwave or infrared drying to shorten drying time and improve energy use (Mierzwa and Szadzińska, 2023; Van Kien et al., 2024). Convective drying is particularly suitable for heat-sensitive compounds like vitamins and essential oils due to its adaptability to low-temperature operation (Tomas-Egea et al., 2021; Castro et al., 2023). Empirical studies confirm its advantages in preserving nutritional and visual qualities in materials such as mushrooms, carrots, and tropical fruits (Ghanbarian et al., 2020; Silva Júnior et al., 2023). The integration of heat recovery systems can further reduce energy consumption by up to 15% (Szadzińska and Mierzwa, 2021).

Nevertheless, alongside these strengths, convective drying faces important limitations that affect both efficiency and product quality. Primarily, the method is time-intensive due to its reliance on surface heat transfer and internal moisture diffusion, often resulting in extended drying durations and elevated energy consumption (EL-Mesery et al., 2023; Szadzińska, Mierzwa, 2021). For instance, drying grapes at 40-60°C with airflow at 2.0 $m \cdot s^{-1}$ may exceed 4,600 minutes (EL-Mesery et al., 2023), while mushrooms require up to 241 minutes at 50°C -nearly tenfold longer than the microwave drying (Szadzińska and Mierzwa, 2021). Longer exposure times are linked to greater cumulative energy losses, especially in systems without heat recovery mechanisms (Ghanbarian et al., 2020); Farias et al., 2020), and can degrade thermolabile compounds such as vitamin C, carotenoids, and polyphenols by up to 30% (Horuz et al., 2017). Additionally, convective drying struggles with non-uniform heat distribution, particularly in materials with irregular geometries, leading to moisture and temperature differentials up to 20% (Hasan et al., 2022). Surface hardening and internal moisture retention are common in fruits like grapes and bananas (Farias et al., 2020; El-Mesery et al., 2023). Overall, the energy consumption ranges from 27 to 70 $MJ \cdot kg^{-1}$ of water removed, which is significantly higher than the advanced drying technologies (Zahoor et al., 2023a).

Microwave Drying

Microwave drying offers a rapid and energy-efficient alternative to conventional convective methods, which often require prolonged thermal exposure and risk quality degradation. Microwave-assisted drying has emerged as an efficient technique for reduction of the drying time and enhancing energy utilization. According to the review by Hay Nguyen et al., (2022), the microwave drying offers volumetric heating, leading to rapid moisture removal and uniform drying. The study highlights its advantages in preserving the nutritional and sensory qualities of heat-sensitive materials, while reducing at the same time the energy consumption compared to conventional methods. This positions microwave-assisted drying as a promising solution for high-efficiency, quality-preserving thermal processing. Operating via volumetric heating, microwaves at 915-2,450 MHz interact with dipolar water molecules to generate heat uniformly from within the material (Mierzwa and Musielak, 2023). This internal heating mechanism significantly accelerates moisture removal, especially in the early drying phase, while minimizing thermal losses (Tepe and Tepe, 2024). As a result, microwave drying improves overall efficiency and enhances the preservation of heat-sensitive compounds.

Microwave drying (MW) is a modern technique highly effective for heat-sensitive materials like medicinal herbs and functional foods. Its primary advantage lies in volumetric heating which reduces drying time by 50-90% compared to hot-air methods (Mierzwa and Musielak, 2023); Hasan et al., 2022). For example, lemon slices dry in 25 minutes vs. several hours by means of convection (Sadeghi et al., 2013), while turmeric dries in one-third of the time (Tepe and Tepe, 2024). Moderate power settings (~100-300 W) enhance drying efficiency and preserve bioactives like polyphenols and flavonoids (Zhu et al., 2023), while cutting energy use by up to 50% (Bhattacharya et al., 2015). Nutritional retention also improves the following: microwave drying preserves 85% of beta-carotene in carrots vs. 60% in case of convection, and curcumin retention reaches 92% in turmeric vs. 78% via hot-air drying (Tepe and Tepe, 2024). Furthermore, its uniform energy distribution ensures consistent moisture content, especially in geometrically simple samples (Zahoor et al., 2023; Mierzwa and Musielak, 2023).

On the other hand, despite these benefits, microwave drying also exhibits notable drawbacks that may compromise the product quality and processing efficiency. Non-uniform heating may create hot spots that cause discoloration, edge burning, or even carbonization, especially in heterogeneous samples like Ganoderma and persimmons (Mierzwa and Musielak, 2023; Cho et al., 2020). Structural shrinkage and poor rehydration are common in dried pumpkin and mushrooms (Mkhize et al., 2023; Szadzińska and Mierzwa, 2021), while color deterioration, such as yellowing or browning, affects peas, plums, and fungi (Chahbani et al., 2018). Rapid heating may also degrade bioactives like polyphenols, vitamin C, and chlorophyll (Zhu et al., 2023), and excessive power reduces antioxidant activity (Bhattacharya et al., 2015). Additionally, MWD systems are costly, complex, and difficult to scale due to uneven energy distribution and high thermal demand (Cao et al., 2020; Zahoor et al., 2023b).

Ultrasound-Assisted Drying

Recent studies have demonstrated the significant potential of ultrasound-assisted drying in enhancing drying performance and product quality. For instance, Xuan Quang-Nguyen et al., (2019) investigated the impact of ultrasound on heat and moisture transfer. The results showed that ultrasound notably increased the thermal and moisture diffusivity while minimizing undesirable color changes, thereby improving drying efficiency and preserving product appearance. Similarly, Hay Nguyen et al., (2022) confirmed that ultrasound integration enhanced drying rates, reduced energy consumption, and maintained the quality attributes of Bo Chinh ginseng. These findings highlight the effectiveness of ultrasound as a non-destructive, energy-efficient drying enhancement technique suitable for high-value herbal and agricultural products. The ultrasound drying (US), typically operating at 20-100 kHz, enhances moisture removal via acoustic cavitation and mechanical oscillations that disrupt capillaries and cell walls (Ding et al., 2024; Khmelev et al., 2024). These effects lower water surface tension and improve the moisture transport. Integrated with conventional drying, The US creates microchannels and a "sponge effect," improving effective diffusivity and mass transfer (Umaña et al., 2022; Yu et al., 2024; Dehghannya et al., 2020). Pretreatment with the US shortens the drying time for carrots by 16.7-25% and apples by 13-17% (Salehi et al., 2023), with energy savings reaching 30-36% (Dehghannya et al., 2020). The US also improves sensory attributes-enhancing brightness and color stability, reducing shrinkage in mushrooms and potatoes, and improving rehydration, especially in apples (Salehi et al., 2023; Zhou, Chen, and Fan, 2024); Dehghannya et al., 2020). However, material-dependent outcomes exist, with some cases showing increased shrinkage in carrots (Salehi et al., 2023). Chemically, US preserves bioactives like polyphenols and vitamin C, with some studies reporting increases in TPC and TFC (Cao et al., 2020; Zhou, Chen, Chitrakar, et al., 2024). While enhanced mass transfer may slightly raise energy dissipation (Zhang et al., 2021), the overall benefits confirm the ultrasound as a valuable tool for efficient and sustainable drying.

Synergistic Mechanism in Convective-Microwave Hybrid Drying Assisted by Ultrasound

The ultrasound-assisted convective–microwave drying (UACMD) is an advanced hybrid technique that synergistically combines surface heating, internal volumetric heating, and mechanical vibration to enhance drying performance and product quality (Tao et al., 2021; Zhou, Chen, and Fan, 2024). Convective drying preserves quality but consumes time and energy (Dehghannya et al., 2019), whereas microwave drying shortens drying time but risks uneven heating and thermal degradation (Szadzińska and Mierzwa, 2021). The ultrasound improves mass transfer by inducing cavitation and microchannel formation, further accelerating moisture diffusion and evaporation (Kroehnke et al., 2018a). As a result, drying durations may be reduced by over 60% for raspberries and more than 66 minutes for carrots, with notable improvements in Deff (Tao et al., 2021; Salehi et al., 2023). The UACMD also enhances energy efficiency (Bhattacharjee et al., 2024), bioactive retention-including 67-69% vitamin C in green chili and up to 45% increase in polyphenol content in mushrooms (Kroehnke et al., 2018a; Szadzińska and Mierzwa, 2021) and supports better texture recovery and rehydration capacity, especially in Ganoderma mushrooms (Inla et al., 2023). The schematic and components of a typical hybrid UACMD system are illustrated in Figure 1.

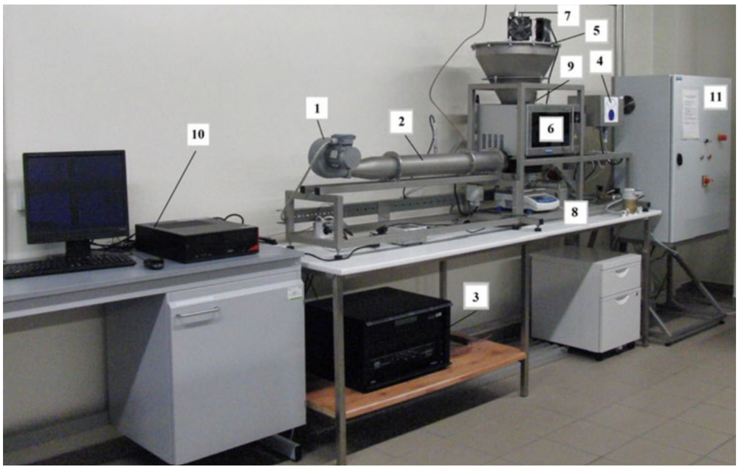
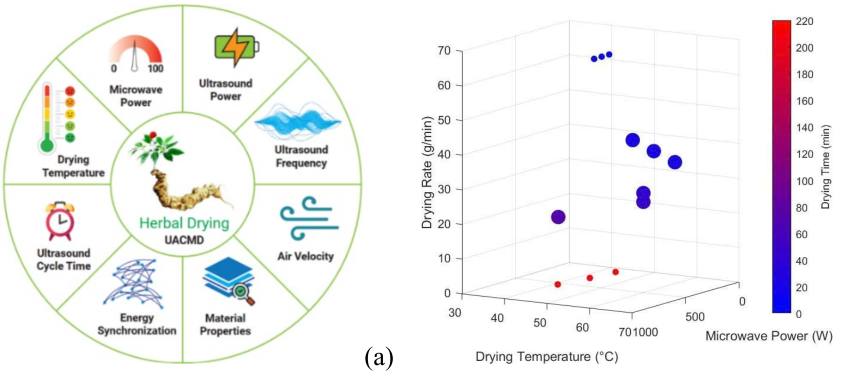


Figure 1. *Photo of the hybrid dryer: 1. Blower, 2. Heater, 3. Ultrasound generator (AUS), 4. Microwave generator, 5. Ultrasound plate, 6. Drying chamber, 7. Ultrasound transducer, 8. Balance, 9. Pyrometer, 10. Computer, 11. Control cupboard. Reproduced from Szadzińska et al., (2020a). Ultrasound- and microwave-assisted intermittent drying of red beetroot*

Effectiveness Analysis of Ultrasound-Supported Convective-Microwave Drying Technology

This section presents and analyzes the overall effectiveness of the ultrasound-assisted convective-microwave drying (UACMD) method based on key criteria such as drying rate, energy efficiency, and post-drying product quality, as summarized in Figure 2(a). The aim is to evaluate the practical application potential of this technology in comparison with conventional and single-mode drying methods.



(a) (b)

Figure 2. (a). Key factors influencing ultrasound-assisted convective–microwave drying (UACMD) technology in medicinal plant processing. (b). The effect of microwave power and drying temperature on drying rate under different ultrasound intensities. Color shading reflects varying ultrasound intensity levels. Data compiled from Tao et al., (2021); Zhu et al., (2024); Mierzwa and Szadzińska, (2023); Szadzińska et al., (2017), and other peer-reviewed sources

Improving Drying Kinetics and Energy Performance

The ultrasound-assisted convective-microwave drying (UACMD) integrates hot-air drying (HAD), microwave drying (MWD), and ultrasound (US) to significantly improve drying kinetics across four key indicators: drying time, drying rate, effective moisture diffusivity (Deff), and energy efficiency. Compared to HAD, pretreatment with MW and US reduced carrot slice drying time from 225 to 158.8 and 193.8 minutes, respectively, with further reductions to 130 minutes under increased MW exposure (Salehi et al., 2023). Raspberry drying time decreased by 79% using a CVMWUS hybrid system, while Ganoderma mushrooms were dried in just 25 minutes- sixfold faster than HAD alone (Inla et al., 2023; Szadzińska et al., 2017).

MW enhances vapor pressure through internal heating, while US induces cavitation and microstreaming, accelerating moisture transfer (Bassey et al., 2021; Huang et al., 2025). In bell peppers, the US-generated vibration accounted for 80% of drying rate improvement (Kroehnke et al., 2018b). Deff values rose substantially - papaya by 28.8%, apples by 1.3 to 2.4 times, and potatoes from 4.89% to 20.7% - due to the enhanced pressure, cell disruption, and microchannel formation (Lima et al., 2024; Zhao et al., 2020; Zhu et al., 2024).

Energy consumption decreased by 20-90% depending on the material, with drying time reduced by 47-87%, while preserving bioactives such as vitamin C and betanin (Musielak et al., 2024; Mierzwa and Musielak, 2023). These findings affirm the UACMD's role in advancing drying performance for medicinal and functional food applications. As further summarized in Table 1, the UACMD demonstrated the most efficient drying performance across multiple trials, achieving up to 50% energy savings and reducing drying time to 15 minutes, while maintaining low power consumption (0.9 kWh). In contrast, traditional convective drying required 180 minutes and consumed 6.0 kWh. As demonstrated in Figure 2(b), the interactive effects of drying temperature, microwave power, and drying rate are depicted, with ultrasound power represented by the sphere size and drying time indicated by a color gradient. The clustering of larger spheres within high drying rate zones suggests that the increased ultrasound intensity significantly enhances moisture removal efficiency. Concurrently, the predominance of blue-colored data points-representing shorter drying durations-in regions of the elevated drying rate and input energy underscores the compounded influence of ultrasound, microwave heating, and thermal convection. These visual patterns collectively validate the synergistic role of ultrasound in the ultrasound-assisted convective-microwave drying (UACMD) systems and further reinforce the superior thermodynamic and economic efficiency associated with hybrid drying technologies.

Table 1.
Comparison of drying methods by time, temperature, energy consumption, and efficiency.

Drying Method	Drying Time (min)	Drying Temperature (°C)	Energy Consumption ($MJ \cdot kg^{-1}$ db)	Energy Savings (%)	References (with raw material)
Convection drying (CH)	180	60	21.6	0%	*Szadzińska and Mierzwa, 2021 (white mushrooms)*
Microwave drying (MW)	30	-	1.1	30%	*Szadzińska and Mierzwa, 2021 (white mushrooms)*
Ultrasound drying (US)	120	-	2.2	20%	*Tao et al., 2021 (blackberry)*
Combined convection - microwave drying (CH-MW)	25	50	4.7	40%	*Szadzińska and Mierzwa, 2021 (white mushrooms)*
Combined convection - microwave - ultrasound drying (CH+MW+US)	15	50	3.2	50%	*Dehghannya et al., 2020 (apple), 2019 (potato), Tao et al., 2021 (blackberry)*

Preservation of Essential Oils and Volatile Aromatic Constituents

The ultrasound-assisted convective–microwave drying (UACMD) offers substantial benefits in preserving essential oils and aroma compounds in medicinal plants, which are highly sensitive to heat and oxidation (Muñoz-Almagro et al., 2021). Conventional hot-air drying (HAD) can cause severe losses up to 65% at 60°C in Melissa officinalis due to gland damage and volatilization. Moreover, HAD often leads to aroma degradation and oxidative byproducts like caryophyllene oxide (Żbik et al., 2023). In contrast, the UACMD synchronizes microwave-driven internal heating with ultrasound-induced microchannel formation, facilitating rapid moisture removal and minimizing heat exposure (Ding et al., 2024; Mierzwa and Szadzińska, 2023). This approach preserved up to 85% of essential oils in Lippia citriodora and improved retention of volatiles such as citral and geraniol, outperforming HAD and microwave alone (Żbik et al., 2023). Additionally, UACMD reduced oxidative byproducts and maintained aroma integrity, making it highly suitable for modern herbal applications (Nowacka et al., 2019).

Preservation of Bioactive Compounds and Nutritional Value

Ultrasound-assisted convective-microwave drying (UACMD) exhibits strong potential for preserving bioactive compounds and nutritional quality in food and medicinal plant materials. By combining thermal energy with ultrasound-induced mechanical enhancement, this technique shortens drying time and minimizes heat-related degradation. For example, carrots treated with US (75 W) and MW (100 W) retained 98% of α-carotene, 97% of β-carotene, and 95% of lutein (Wiktor and Witrowa-Rajchert, 2020), while bell pepper samples preserved up to 69% of vitamin C (Szadzińska et al., 2016). Mild drying conditions in feijoa and broccoli similarly resulted in high vitamin C retention (Castro et al., 2023; Cao et al., 2020).

Enhanced preservation of polyphenols and flavonoids was observed in mushrooms and hawthorn fruit (Abbaspour-Gilandeh et al., 2021), with low-pressure drying increasing the polyphenol content by up to 40% via cavitation-driven cell disruption (Żbik et al., 2023). Combined ultrasound osmotic dehydration and pulsed microwave drying further improved antioxidant capacity and inhibited PPO and POD enzymes in kiwifruit (Yu et al., 2024).

Additional studies confirm the beneficial effects of ultrasound on the phenolic content in mushrooms, lotus root, and onions (Szadzińska and Mierzwa, 2021; Yu et al., 2024; Ghanbarian et al., 2020), aroma compound retention in perilla leaves (Ding et al., 2024), and dietary fiber enhancement in pomelo peel (Muñoz-Almagro et al., 2021). However, excessive microwave power may degrade polyphenols, as noted in carrots (Salehi et al., 2023). These findings suggest that preservation outcomes depend on the material type, drying conditions, and process optimization.

Enhancement of Color and Structural Integrity

The ultrasound-assisted convective-microwave drying (UACMD) offers notable advantages in preserving color and microstructure in dried plant materials. High temperature drying often degrades chlorophyll, leading to color loss, while controlled UACMD processes reduce both drying time and thermal exposure, thereby maintaining natural pigmentation (Nurhaslina et al., 2022). In kale, UACMD at 50°C and moderate ultrasound-microwave settings significantly lowered ΔE values compared to hot-air drying, indicating better retention of green coloration (Mierzwa and Szadzińska, 2023). Ultrasound-induced cavitation creates microchannels in tissues, and microwaves enable uniform internal heating-together preventing overheating and pigment breakdown. Additional studies on apples, peppers, and vegetables showed that UACMD enhanced tissue elasticity, reduced shrinkage by 15%, and preserved flavonoid levels through uniform thermal distribution and minimized moisture gradients (Zhou, et al., 2024; Musielak et al., 2024). Ultrasound in low-pressure systems also reduced the mechanical stress, improved chlorophyll retention and surface texture (Żbik et al., 2023). Overall, the UACMD offers superior outcomes compared to conventional drying methods by simultaneously optimizing visual quality, tissue integrity, and drying efficiency.

Obstacles and Future Directions for Advancement

Despite its promising performance in the product quality and energy efficiency, the UACMD still faces key technical and research challenges that limit its widespread application in medicinal plant processing.

Despite the advantages of the ultrasound-assisted convective-microwave drying (UACMD), several limitations exist. High microwave power may degrade sensitive bioactives, reducing β-carotene, TPC, TFC, and antioxidant activity in carrots (Wiktor & Witrowa-Rajchert, 2020), while CVMW100W treatments resulted in lower phenolic retention (Kroehnke et al., 2018b). However, prolonged ultrasound exposure may oxidize polysaccharides (Li et al., 2021), and vacuum microwave drying can diminish vitamin C and chlorophyll in okra (Zang et al., 2023). Similar losses have been observed in apples and black grapes dried using ultrasound–hot-air combinations (El-Mesery et al., 2023).

Controlling and optimizing UACMD parameters remains challenging. Studies focusing on bioactive peptide preservation are limited (Muñoz-Almagro et al., 2021), while non-intuitive interactions-such as those affecting TPC/TFC in Chinese pecans (Zhang et al., 2021)-complicate the process design. Ultrasound frequency strongly affects efficiency: low frequencies (20-40 kHz) enhance cavitation but risk tissue damage, whereas higher frequencies (>50 kHz) are safer but less effective (Nurhaslina et al., 2022). Improper synchronization of airflow, temperature, and MW–US input may induce structural deformation (Musielak et al., 2024), while microwave "hot spots" compromise uniformity (Nurhaslina et al., 2022). Without precise control, energy savings may be minimal (Szadzińska et al., 2019).

Physical and sensory drawbacks include shrinkage, hardness, and color distortion-such as elevated ΔE values in Ganoderma mushrooms (Inla et al., 2023) or reduced brightness in scallions (Zhou, et al., 2024). Phenolic loss leads to browning and flavor decline (Wu et al., 2024), while key volatiles and pectin structures may degrade in perilla leaves and goji berries (Ding et al., 2024; Zhu et al., 2024).

In addition to the product-quality concerns, the UACMD faces practical challenges related to industrial adoption. Its reliance on specialized, high-cost hybrid equipment limits integration with existing hot-air systems, reducing scalability (Musielak et al., 2024). Moreover, the need for precise control and skilled operation, along with potential increases in energy demand, raises sustainability concerns (Tao et al., 2021; Szadzińska et al., 2020).

Future Directions for Advancement

The ultrasound-microwave drying is increasingly recognized for its ability to reduce drying time, energy consumption, and bioactive compound loss in medicinal herbs. To unlock its full industrial potential, several areas warrant focused development. First, constructing accurate mathematical and experimental models will be essential for predicting critical quality attributes such as moisture content, nutrient retention, microstructure, and color-allowing for better process control, reproducibility, and transferability to large-scale systems. Alongside modeling, optimizing key operational parameters-including microwave power, ultrasound intensity, and convective temperature, is vital to strike a balance between drying efficiency and the preservation of thermosensitive constituents like β-carotene and vitamin C, while also considering cost-effectiveness in industrial setups.

Furthermore, the integration of digital technologies such as hyperspectral imaging, computer vision, and artificial intelligence is expected to play a transformative role in monitoring drying in real time, enabling intelligent control and facilitating industrial scalability. At the same time, practical issues such as retrofitting hybrid equipment into conventional hot-air dryers, ensuring operator training, and addressing maintenance complexity must be resolved to support reliable industrial deployment. Equally important is the need for targeted research on specific categories of medicinal materials-ranging from leaves and roots to fungi and essential oil-rich botanicals- to guide process customization based on structural and chemical characteristics and to meet regulatory requirements in herbal medicine production.

Together, these advances will help establish ultrasound–microwave drying as a sustainable, high-performance solution tailored for the next generation of herbal processing applications.

Conclusion

The ultrasound-assisted convective-microwave drying (UACMD) is a promising technique for medicinal herbs and food products, offering reduced drying time and energy use through synergistic mechanisms: ultrasound-enhanced mass transfer, microwave volumetric heating, and hot-air convection. It effectively preserves bioactive compounds such as vitamin C, polyphenols, and carotenoids, while improving texture and rehydration capacity. Although color changes are possible, they can be effectively minimized through optimized process conditions, ensuring visual quality alongside functional and nutritional preservation. To unlock the UACMD's full potential, further studies on drying kinetics and bioactive stability are needed. In-depth research into the drying mechanisms specific to each type of medicinal plant will enable precise process optimization, ensuring consistent product quality at scale.

Author Contributions:
Conceptualization: N.H.V and H.N; Methodology: N.H.V and H.N; Software: N.H.V; Formal analysis: N.H.V and D.A.L; Investigation: N.H.V and D.A.L; Resources: N.H.V and H.N; Data curation: N.H.V, D.A.L, and H.N; Writing - original draft: N.H.V, D.A.L, and H.N; Supervision: N.H.V and H.N. All authors have read and agreed to the published version of the manuscript. Authorship is limited to those who have made a significant contribution to the reported study.

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References

Abbaspour-Gilandeh, Y., Kaveh, M., Fatemi, H., & Aziz, M. (2021). Combined hot air, microwave, and infrared drying of hawthorn fruit: Effects of ultrasonic pretreatment on drying time, energy, qualitative, and bioactive compounds' properties. *Foods*, *10*(5). https://doi.org/10.3390/foods10051006.

Bassey, E. J., Cheng, J. H., & Sun, D. W. (2021). Novel nonthermal and thermal pretreatments for enhancing drying performance and improving quality of fruits and vegetables. *Trends in Food Science & Technology*, *112*, 137–148. https://doi.org/10.1016/J.TIFS.2021.03.045.

Bhattacharjee, S., Mohanty, P., Sahu, J. K., & Sahu, J. N. (2024). A critical review on drying of food materials: Recent progress and key challenges. *International Communications in Heat and Mass Transfer*, *158*, 107863. https://doi.org/10.1016/J.ICHEATMASSTRANSFER.2024.107863.

Bhattacharya, M., Srivastav, P. P., & Mishra, H. N. (2015). Thin-layer modeling of convective and microwave-convective drying of oyster mushroom (Pleurotus ostreatus). *Journal of Food Science and Technology*, *52*(4), 2013–2022. https://doi.org/10.1007/s13197-013-1209-2.

Cao, Y., Tao, Y., Zhu, X., Han, Y., Li, D., Liu, C., Liao, X., & Show, P. L. (2020). Effect of microwave and air-borne ultrasound-assisted air drying on drying kinetics and phytochemical properties of broccoli floret. *Drying Technology*, *38*(13), 1733–1748. https://doi.org/10.1080/07373937.2019.1662437.

Casaverde-Pacherrez, L. A., Téllez-Pérez, C., Besombes, C., Marcelo-Aldana, D., Allaf, K., & Vásquez-Díaz, E. (2022). Effect of Swell-Drying on Mango (Mangifera indica) Drying Kinetics. *Foods*, *11*(15). https://doi.org/10.3390/foods11152220.

Castro, A. M., Díaz, L. E., Quintanilla-Carvajal, M. X., Mayorga, E. Y., & Moreno, F. L. (2023). Convective drying of feijoa (Acca sellowiana Berg): A study on bioactivity, quality, and drying parameters. *LWT*, *186*. https://doi.org/10.1016/j.lwt.2023.115209.

Chahbani, A., Fakhfakh, N., Balti, M. A., Mabrouk, M., El-Hatmi, H., Zouari, N., & Kechaou, N. (2018). Microwave drying effects on drying kinetics, bioactive compounds and antioxidant activity of green peas (Pisum sativum L.). *Food Bioscience*, *25*, 32–38. https://doi.org/10.1016/j.fbio.2018.07.004.

Cho, J. S., Choi, J. Y., & Moon, K. D. (2020). Hyperspectral imaging technology for monitoring of moisture contents of dried persimmons during drying process. *Food Science and Biotechnology*, *29*(10), 1407–1412. https://doi.org/10.1007/s10068-020-00791-x.

Dehghannya, J., Aghazade-Khoie, E., Khakbaz Heshmati, M., & Ghanbarzadeh, B. (2020). Influence of Ultrasound Intensification on the Continuous and Pulsed Microwave during Convective Drying of Apple. *International Journal of Fruit Science*, *20*(S3), S1751–S1764. https://doi.org/10.1080/15538362.2020.1830919.

Dehghannya, J., Kadkhodaei, S., Heshmati, M. K., & Ghanbarzadeh, B. (2019). Ultrasound-assisted intensification of a hybrid intermittent microwave - hot air drying process of potato: Quality aspects and energy consumption. *Ultrasonics*, *96*, 104–122. https://doi.org/10.1016/J.ULTRAS.2019.02.005.

Ding, T., Li, Y., Wang, J., Song, F., Jin, G., Li, Z., Meng, X., Song, C., & Song, W. (2024). Effects of ultrasound blanching followed by hot air-coupled microwave drying on the quality of perilla leaves. *Journal of Stored Products Research*, *109*. https://doi.org/10.1016/j.jspr.2024.102419.

El-Mesery, H. S., Farag, H. A., Kamel, R. M., & Alshaer, W. G. (2023). Convective hot air drying of grapes: drying kinetics, mathematical modeling, energy, thermal analysis. *Journal of Thermal Analysis and Calorimetry*, *148*(14), 6893–6908. https://doi.org/10.1007/s10973-023-12195-0.

EL-Mesery, H. S., Kamel, R. M., & Alshaer, W. G. (2023). Enhancement of grapes convective drying by application of different airflow direction techniques. *Heat and Mass Transfer/Waerme- Und Stoffuebertragung*, *59*(4), 699–712. https://doi.org/10.1007/s00231-022-03288-x.

Farias, R. P., Gomez, R. S., Silva, W. P., Silva, L. P. L., Oliveira Neto, G. L., Santos, I. B., Carmo, J. E. F., Nascimento, J. J. S., & Lima, A. G. B. (2020). Heat and mass transfer, and volume variations in banana slices during convective hot air drying: An experimental analysis. *Agriculture (Switzerland)*, *10*(10), 1–14. https://doi.org/10.3390/agriculture10100423.

Ghanbarian, D., Torki-Harchegani, M., Sadeghi, M., & Pirbalouti, A. G. (2020). Ultrasonically improved convective drying of peppermint leaves: Influence on the process time and energetic indices. *Renewable Energy*, *153*, 67–73. https://doi.org/10.1016/j.renene.2019.10.024.

Hasan, M. M., Uddin, M. J., & Nasrin, R. (2022). Exothermic chemical reaction of magneto-convective nanofluid flow in a square cavity. *International Journal of Thermofluids*, *16*. https://doi.org/10.1016/j.ijft.2022.100236.

Horuz, E., Jaafar, H. J., & Maskan, M. (2017). Ultrasonication as pretreatment for drying of tomato slices in a hot air–microwave hybrid oven. *Drying Technology*, *35*(7), 849–859. https://doi.org/10.1080/07373937.2016.1222538.

Huang, J., Zhang, M., Mujumdar, A. S., & Li, C. (2025). AI-based processing of future prepared foods: Progress and prospects. In *Food Research International* (Vol. 201). Elsevier Ltd. https://doi.org/10.1016/j.foodres.2025.115675.

Inla, K., Bunchan, S., Krittacom, B., & Luampon, R. (2023). Drying behavior, color change and rehydration of lingzhi mushroom (Ganoderma lucidum) under convection-assisted microwave drying. *Case Studies in Thermal Engineering*, *49*. https://doi.org/10.1016/j.csite.2023.103348

Khmelev, V. N., Shalunov, A. V, Terent'ev, S. A., Golykh, R. N., & Nesterov, V. A. (2024). Revealing and Studying of the Mechanism of Moisture Removal from Materials on Exposure to Ultrasonic Noncontact Effect. *Journal of Engineering Physics and Thermophysics*, *97*(4), 925–937. https://doi.org/10.1007/s10891-024-02962-7.

Kroehnke, J., Szadzińska, J., Stasiak, M., Radziejewska-Kubzdela, E., Biegańska-Marecik, R., & Musielak, G. (2018a). Ultrasound- and microwave-assisted convective drying of carrots – Process kinetics and product's quality analysis. *Ultrasonics Sonochemistry*, *48*, 249–258. https://doi.org/10.1016/j.ultsonch.2018.05.040.

Kroehnke, J., Szadzińska, J., Stasiak, M., Radziejewska-Kubzdela, E., Biegańska-Marecik, R., & Musielak, G. (2018b). Ultrasound- and microwave-assisted convective drying of carrots – Process kinetics and product's quality analysis. *Ultrasonics Sonochemistry*, *48*, 249–258. https://doi.org/10.1016/j.ultsonch.2018.05.040.

Lima, R. E., Coradi, P. C., Rodrigues, D. M., Teodoro, P. E., Teodoro, L. P. R., & de Oliveira, D. P. (2024). Monitoring and predicting the quality of soybeans for different drying and storage technologies on a real scale using sensors and Machine Learning models. *Journal of Stored Products Research*, *108*. https://doi.org/10.1016/j.jspr.2024.102386.

Mierzwa, D., & Musielak, G. (2023). Convective–Microwave–IR Hybrid Drying of Kaolin Clay—Kinetics of Process. *Applied Sciences (Switzerland)*, *13*(13). https://doi.org/10.3390/app13137451

Mierzwa, D., & Szadzińska, J. (2023). An Investigation of the Use of Microwaves and Airborne Ultrasound in the Convective Drying of Kale: Process Efficiency and Product Characteristics. *Sustainability (Switzerland)*, *15*(23). https://doi.org/10.3390/su152316200.

Mkhize, X., Nkosi, N., Zondi, L., & Tumba, K. (2023). Convective drying of pumpkin: Brief literature review and new data for organically produced indigenous pumpkin (Cucurbita pepo L.) over an expanded temperature range. *Journal of Agriculture and Food Research*, *14*. https://doi.org/10.1016/j.jafr.2023.100800.

Muñoz-Almagro, N., Morales-Soriano, E., Villamiel, M., & Condezo-Hoyos, L. (2021). Hybrid high-intensity ultrasound and microwave treatment: A review on its effect on quality and bioactivity of foods. In *Ultrasonics Sonochemistry* (Vol. 80). Elsevier B.V. https://doi.org/10.1016/j.ultsonch.2021.105835.

Musielak, G., Mieszczakowska-Frąc, M., & Mierzwa, D. (2024). Convective Drying of Apple Enhanced with Microwaves and Ultrasound—Process Kinetics, Energy Consumption, and Product Quality Approach. *Applied Sciences (Switzerland)*, *14*(3). https://doi.org/10.3390/app14030994.

Nguyen, H., Le, Q. H., Le, T. D., & Pham, V. K. (2022a). Experimental Research to Determine the Effect of Ultrasound in Drying Bo Chinh Ginseng by Ultrasound-Assisted Heat Pump Drying Method. *Applied Sciences (Switzerland)*, *12*(22). https://doi.org/10.3390/app122211525.

Nguyen, H., Le, Q. H., Le, T. D., & Pham, V. K. (2022b). Experimental Research to Determine the Effect of Ultrasound in Drying Bo Chinh Ginseng by Ultrasound-Assisted Heat Pump Drying Method. *Applied Sciences (Switzerland)*, *12*(22). https://doi.org/10.3390/app122211525.

Nguyen, X. Q., Le, A. D., Nguyen, N. P., & Nguyen, H. (2019). Thermal Diffusivity, Moisture Diffusivity, and Color Change of Codonopsis javanica with the Support of the Ultrasound for Drying. *Journal of Food Quality*, *2019*. https://doi.org/10.1155/2019/2623404.

Nowacka, M., Wiktor, A., Anuszewska, A., Dadan, M., Rybak, K., & Witrowa-Rajchert, D. (2019). The application of unconventional technologies as pulsed electric field, ultrasound and microwave-vacuum drying in the production of dried cranberry snacks. *Ultrasonics Sonochemistry*, *56*, 1–13. https://doi.org/10.1016/j.ultsonch.2019.03.023.

Nurhaslina, C. R., Andi Bacho, S., & Mustapa, A. N. (2022). Review on drying methods for herbal plants. *Materials Today: Proceedings*, *63*, S122–S139. https://doi.org/10.1016/j.matpr.2022.02.052

Sadeghi, M., Mirzabeigi Kesbi, O., & Mireei, S. A. (2013). Mass transfer characteristics during convective, microwave and combined microwave-convective drying of lemon slices. *Journal of the Science of Food and Agriculture*, *93*(3), 471–478. https://doi.org/10.1002/jsfa.5786.

Salehi, F., Goharpour, K., & Razavi Kamran, H. (2023). Effects of ultrasound and microwave pretreatments of carrot slices before drying on the color indexes and drying rate. *Ultrasonics Sonochemistry*, *101*. https://doi.org/10.1016/j.ultsonch.2023.106671.

Silva Júnior, M. A. V, Leite, M. A., & Dacanal, G. C. (2023). *Modelling of convective drying of potatoes polyhedrons*. *19*(12), 605–617. https://doi.org/doi:10.1515/ijfe-2023-0016

Szadzińska, J., Kowalski, S. J., & Stasiak, M. (2016). Microwave and ultrasound enhancement of convective drying of strawberries: Experimental and modeling efficiency. *International Journal of Heat and Mass Transfer*, *103*, 1065–1074. https://doi.org/10.1016/j.ijheatmasstransfer.2016.08.001

Szadzińska, J., Łechtańska, J., Kowalski, S. J., & Stasiak, M. (2017). The effect of high power airborne ultrasound and microwaves on convective drying effectiveness and quality of green pepper. *Ultrasonics Sonochemistry*, *34*, 531–539. https://doi.org/10.1016/J.ULTSONCH.2016.06.030.

Szadzińska, J., Łechtańska, J., Pashminehazar, R., Kharaghani, A., & Tsotsas, E. (2019). Microwave- and ultrasound-assisted convective drying of raspberries: Drying kinetics and microstructural changes. *Drying Technology*, *37*(1), 1–12. https://doi.org/10.1080/07373937.2018.1433199

Szadzińska, J., & Mierzwa, D. (2021). The influence of hybrid drying (microwave-convective) on drying kinetics and quality of white mushrooms. *Chemical Engineering and Processing - Process Intensification*, *167*. https://doi.org/10.1016/j.cep.2021.108532.

Szadzińska, J., Mierzwa, D., Pawłowski, A., Musielak, G., Pashminehazar, R., & Kharaghani, A. (2020a). Ultrasound- and microwave-assisted intermittent drying of red beetroot. *Drying Technology*, *38*(1–2), 93–107. https://doi.org/10.1080/07373937.2019.1624565.

Szadzińska, J., Mierzwa, D., Pawłowski, A., Musielak, G., Pashminehazar, R., & Kharaghani, A. (2020b). Ultrasound- and microwave-assisted intermittent drying of red beetroot. *Drying Technology*, *38*(1–2), 93–107. https://doi.org/10.1080/07373937.2019.1624565.

Tao, Y., Li, D., Siong Chai, W., Show, P. L., Yang, X., Manickam, S., Xie, G., & Han, Y. (2021). Comparison between airborne ultrasound and contact ultrasound to intensify air drying of blackberry: Heat and mass transfer simulation, energy consumption and quality evaluation. *Ultrasonics Sonochemistry*, *72*. https://doi.org/10.1016/j.ultsonch.2020.105410.

Tepe, T. K., & Tepe, F. B. (2024). Improvement of pear slices drying by pretreatments and microwave-assisted convective drying method: drying characteristics, modeling of artificial neural network, principal component analysis of quality parameters. *Journal of Thermal Analysis and Calorimetry*, *149*(14), 7313–7328. https://doi.org/10.1007/s10973-024-13280-8.

Tomas-Egea, J. A., Traffano-Schiffo, M. V., Castro-Giraldez, M., & Fito, P. J. (2021). Hot air and microwave combined drying of potato monitored by infrared thermography. *Applied Sciences (Switzerland)*, *11*(4), 1–12. https://doi.org/10.3390/app11041730.

Umaña, M., Calahorro, M., Eim, V., Rosselló, C., & Simal, S. (2022). Measurement of microstructural changes promoted by ultrasound application on plant materials with different porosity. *Ultrasonics Sonochemistry*, *88*. https://doi.org/10.1016/j.ultsonch.2022.106087.

Wiktor, A., & Witrowa-Rajchert, D. (2020). Drying kinetics and quality of carrots subjected to microwave-assisted drying preceded by combined pulsed electric field and ultrasound treatment. *Drying Technology*, *38*(1–2), 176–188. https://doi.org/10.1080/07373937.2019.1642347.

Wu, T., Duan, Z., & Wang, C. (2024). Effects of microwave drying on color change, phenolic substance content and phenolase activity of different parts of persimmon slices. *Journal of Food Measurement and Characterization*, *18*(1), 357–369. https://doi.org/10.1007/s11694-023-02162-6.

Van Kien, P., Tan, N. T., Nghia, P. H., & Hay, N. (2024). Heat and mass transfer in infrared assisted heat pump drying of purple yam. *Agricultural Engineering*, *28*(1), 71-84. https://doi.org/10.2478/agriceng- 2024-0006.

Yoon, W. (2024). Special Issue on "Drying Kinetics and Quality Control in Food Processing." *Processes*, *12*, 1698. https://doi.org/10.3390/pr12081698.

Yu, Y., Chen, Y., Wang, Y., Sun, X., Guo, Y., Su, D., & Xu, H. (2024). Unlocking new drying potential for Lotus root: Ultrasonic osmotic dehydration and microwave hot air drying based on phenolic retention and microstructure. *Innovative Food Science and Emerging Technologies*, *97*. https://doi.org/10.1016/j.ifset.2024.103824.

Zahoor, I., Mir, T. A., Ayoub, W. S., Farooq, S., & Ganaie, T. A. (2023a). Recent applications of microwave technology as novel drying of food – Review. *Food and Humanity*, *1*, 92–103. https://doi.org/10.1016/j.foohum.2023.05.001.

Zahoor, I., Mir, T. A., Ayoub, W. S., Farooq, S., & Ganaie, T. A. (2023b). Recent applications of microwave technology as novel drying of food – Review. *Food and Humanity*, *1*, 92–103. https://doi.org/10.1016/J.FOOHUM.2023.05.001.

Zang, Z., Zhang, Q., Huang, X., Jiang, C., He, C., & Wan, F. (2023). Effect of Ultrasonic Combined with Vacuum Far-infrared on the Drying Characteristics and Physicochemical Quality of Angelica sinensis. *Food and Bioprocess Technology*, *16*(11), 2455–2470. https://doi.org/10.1007/s11947-023-03076-3.

Żbik, K., Górska-Horczyczak, E., Onopiuk, A., Kurek, M., & Zalewska, M. (2023). Vacuum and convection drying effects on volatile compounds profile and physicochemical properties of selected herbs from Lamiaceae family. *European Food Research and Technology*, *249*(10), 2569–2581. https://doi.org/10.1007/s00217-023-04309-7.

Zhang, J., Li, M., Ding, Z., Wang, C., & Cheng, J. (2021). Evaluation of ultrasound-assisted microwave hot air convective drying Chinese hickory—Drying kinetics and product's quality properties. *Journal of Food Process Engineering*, *44*(11). https://doi.org/10.1111/jfpe.13842.

Zhao, Y., Zheng, Y., Li, Z., Jiang, Y., Zhuang, W., Zheng, B., & Tian, Y. (2020). Effects of ultrasonic pretreatments on thermodynamic properties, water state, color kinetics, and free amino acid composition in microwave vacuum dried lotus seeds. *Drying Technology*, *38*(4), 534–544. https://doi.org/10.1080/07373937.2019.1587618.

Zhou, S., Chen, W., Chitrakar, B., & Fan, K. (2024). Ultrasound Technology for Enhancing Drying Efficiency and Quality of Fruits and Vegetables: A Review. In *Food and Bioprocess Technology*. Springer. https://doi.org/10.1007/s11947-024-03379-z.

Zhou, S., Chen, W., & Fan, K. (2024). Recent advances in combined ultrasound and microwave treatment for improving food processing efficiency and quality: A review. *Food Bioscience*, *58*, 103683. https://doi.org/https://doi.org/10.1016/j.fbio.2024.103683.

Zhu, R., Ma, X., Li, D., Han, Y., Manickam, S., Jiao, Y., Flores, E. M. M., & Tao, Y. (2024). Three-dimensional mass transfer modeling and phenolic chemistry exploration for ultrasound-assisted and microwave drying of goji berry. *Food Research International*, *193*. https://doi.org/10.1016/j.foodres.2024.114826.

Zhu, R., Shen, J., Law, C. L., Ma, X., Li, D., Han, Y., Kiani, H., Manickam, S., & Tao, Y. (2023). Combined calcium pretreatment and ultrasonic/microwave drying to dehydrate black chokeberry: Novel mass transfer modeling and metabolic pathways of polyphenols. *Innovative Food Science & Emerging Technologies*, *83*, 103215. https://doi.org/10.1016/J.IFSET.2022.103215.

ZINTEGROWANE SUSZENIE KONWEKCYJNO–MIKROFALOWE WSPOMAGANE ULTRADŹWIĘKAMI DO DEHYDRATACJI ROŚLIN LECZNICZYCH

Streszczenie. Zintegrowane suszenie konwekcyjno – mikrofalowe wspomagane ultradźwiękami (UMCD) do dehydratacji roślin leczniczych jest wschodzącą hybrydową metodą suszenia, która łączy w sobie konwekcje gorącym powietrzem, ogrzewanie mikrofalowe oraz kawitacje ultradźwiękami celem zwiększenia transferu wilgoci i zachowania bioaktywnych składników w ziołach leczniczych. Niniejszy przegląd stanowi streszczenie zalet tej metody, do których zalicza się redukcję czasu suszenia o 30-80%, poprawę wydajności energetycznej oraz lepszą retencję przeciwutleniaczy, olejków eterycznych i koloru. Jednak pozostają wyzwania, takie jak degradacja termiczna oraz złożoność skalowania. Przyszłe osiągnięcia kładą nacisk na integrację inteligentnych elementów sterowania (sztucznej inteligencji, widzenia komputerowego i obrazowania hiperspektralnego) oraz dostosowywanie protokołów do konkretnych rodzajów ziół, co czyni UACMD zrównoważonym i wydajnym rozwiązaniem w zakresie nowoczesnego suszenia ziół.

Słowa kluczowe: Zioła lecznicze, suszenie hybrydowe, konserwacja związków bioaktywnych, suszenie za pomocą ultradźwięków, suszenie mikrofalowe