



## Advances in microwave drying and vacuum-based drying technologies for apple preservation: Quality retention and shelf-life enhancement of apple - A detailed review

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### Abstract

Apple (*Malus domestica*) is one of the most widely consumed fruits globally owing to its nutritional value, sensory characteristics and health-promoting bioactive compounds. However, its high moisture content and active metabolic processes make it highly susceptible to microbial spoilage, enzymatic browning and quality deterioration during storage and distribution. Drying is an effective preservation technique that extends shelf life by reducing moisture content and water activity, thereby inhibiting microbial growth and slowing biochemical reactions. In recent years, advanced drying technologies such as microwave drying, vacuum drying and vacuum-microwave drying have gained considerable attention as alternatives to conventional hot-air drying due to their superior drying efficiency and product quality retention. This review critically examines the principles, drying mechanisms, process kinetics and quality characteristics associated with microwave and vacuum-based drying methods for apple preservation. Microwave drying utilizes volumetric heating to accelerate moisture removal, resulting in significantly reduced drying times and improved energy efficiency. Vacuum drying operates under reduced pressure, enabling moisture evaporation at lower temperatures and minimizing thermal degradation of heat-sensitive components.

The Vacuum-microwave drying combines the advantages of both technologies by enhancing drying rates while preserving color, texture, nutritional compounds and antioxidant activity. Comparative analysis of published studies indicates that vacuum-microwave drying generally provides the best balance between drying efficiency and product quality, producing dried apple products with superior rehydration capacity, reduced oxidation and enhanced storage stability. The review further discusses the influence of process parameters, including microwave power, vacuum level, drying temperature and pretreatment methods, on product quality and shelf-life performance. Current challenges related to equipment cost, process optimization and industrial-scale implementation are also highlighted. Overall, microwave and vacuum-based drying technologies represent promising approaches for the production of high-quality dried apple products with extended shelf life, improved nutritional retention and enhanced commercial value. Future research should focus on hybrid drying strategies, intelligent process control and comprehensive storage studies to support large-scale industrial adoption.

**Keywords:** Apple drying, microwave drying, vacuum drying, vacuum-microwave drying, shelf life and food preservation

### Introduction

Apple (*Malus domestica* Borkh.) is one of the most widely cultivated and consumed fruit crops worldwide due to its high nutritional value, pleasant flavor and rich content of bioactive compounds, including polyphenols, flavonoids, dietary fiber, vitamins and antioxidants. Apples contribute significantly to human health by reducing the risk of cardiovascular diseases, diabetes, obesity and certain forms of cancer owing to their antioxidant and anti-inflammatory properties (Boyer & Liu, 2004; Wojdyło *et al.*, 2021) [4, 31]. According to the Food and Agriculture Organization (FAO), global apple production exceeds 95 million tonnes annually, making apple one of the most economically important fruit commodities in the world. Major apple-producing countries include China, the United States, India, Turkey and Poland. Despite high production levels, substantial post-harvest losses occur during storage, transportation and marketing

due to the fruit's high moisture content and active physiological metabolism (FAO, 2024).

Fresh apples typically contain 80–86% moisture and remain metabolically active even after harvest. Their high water content creates favorable conditions for microbial growth, enzymatic browning, respiration and biochemical degradation, leading to quality deterioration and reduced shelf life (Kader, 2002; Rahman, 2009) [14, 23]. In developing countries, post-harvest losses of fruits and vegetables can reach 20–40%, resulting in significant economic losses and reduced food availability (Fellows, 2017) [8]. Therefore, the development of efficient preservation technologies capable of extending shelf life while maintaining nutritional and sensory quality remains an important research priority for the food processing industry.

Drying is among the oldest and most effective food preservation methods used to reduce moisture content and

water activity, thereby inhibiting microbial growth and slowing enzymatic and biochemical reactions. The reduction of water activity significantly improves product stability and allows long-term storage without refrigeration (Mujumdar, 2014) [20]. Traditionally, hot-air drying has been widely employed for fruit dehydration due to its simplicity and relatively low operational cost. However, numerous studies have reported that prolonged exposure to elevated temperatures during conventional drying can result in undesirable changes in color, texture, flavor, nutrient composition and rehydration characteristics (Lewicki, 2006; Doymaz, 2011) [6, 15]. Furthermore, conventional drying methods are often associated with long processing times and high energy consumption, limiting their efficiency in modern food processing systems. Vedantam Sai Krishna *et al.* (2025) [39] was reviewed on phase change material incorporated in convective solar dryers. Sai Krishna (2025) [39] was also studied Effect of pre-treatments on drying and rehydration characteristics of Amla (*Phyllanthus emblica* L.) under direct solar radiation. Vinayak *et al.*, (2026) [41] has developed and evaluated a Bluetooth-enabled grain inversion machine for efficient grain drying for small and marginal farmers. Sai Krishna *et al.* (2025) [39] has reviewed on indirect drying using evacuated tubes.

To overcome these limitations, advanced drying technologies have gained increasing attention over the past two decades. Among these technologies, microwave drying and vacuum-based drying methods have emerged as promising alternatives due to their ability to improve drying efficiency while preserving product quality. Microwave drying utilizes electromagnetic energy to generate volumetric heating within the food matrix, enabling rapid moisture removal and significantly reducing drying time compared with conventional methods (Maskan, 2000; Zhang *et al.*, 2014) [17, 34]. The internal generation of heat promotes faster moisture migration from the interior to the surface of the product, resulting in enhanced drying rates and improved energy efficiency. Several studies have demonstrated that microwave drying can effectively preserve color, texture, antioxidant activity and phenolic compounds when process parameters are properly optimized (Darvishi *et al.*, 2014; Feng *et al.*, 2015) [5, 10].

Vacuum drying, on the other hand, operates under reduced pressure conditions, lowering the boiling point of water and allowing dehydration at comparatively lower temperatures. This feature makes vacuum drying particularly suitable for heat-sensitive food materials such as fruits and vegetables (Ratti, 2001) [25]. Reduced oxygen availability during vacuum processing minimizes oxidative degradation, enzymatic browning and nutrient losses, leading to superior product quality and enhanced shelf-life stability (Lewicki & Jakubczyk, 2004) [16]. More recently, vacuum-microwave drying has attracted considerable research interest because it combines the rapid heating characteristics of microwave energy with the protective environment provided by vacuum conditions. Studies conducted by Zhang *et al.* (2019), Song *et al.* (2018) [27, 37] and several recent researchers have reported that vacuum-microwave drying produces dried apple products with superior color retention, porous microstructure, improved rehydration capacity and higher

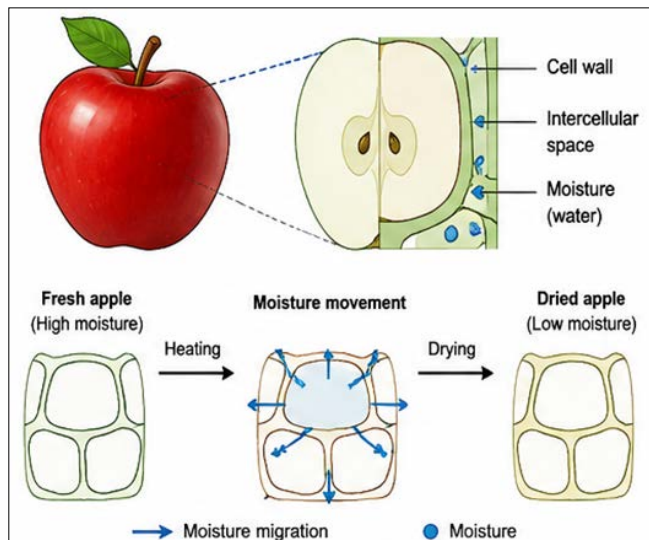
retention of bioactive compounds compared with conventional drying methods.

Recent investigations have also focused on process optimization, mathematical modeling, energy efficiency analysis and quality prediction during advanced drying operations. The integration of intelligent sensors, artificial intelligence, machine learning algorithms and real-time monitoring systems has further enhanced process control and product quality assessment in modern drying technologies (Chen *et al.*, 2023) [42]. Additionally, hybrid drying approaches combining microwave, vacuum, infrared and ultrasonic technologies have shown promising potential for improving drying performance while reducing energy consumption and processing costs.

Recent advancements in food dehydration technologies have focused on improving energy efficiency, product quality and process sustainability. Contemporary research has emphasized the development of innovative drying approaches, including microwave-assisted drying, vacuum drying, vacuum-microwave drying, infrared-assisted drying, ultrasonic-assisted drying and hybrid drying systems. Reis *et al.* (2022) [26] reported that advanced drying technologies significantly improve color retention, microstructural integrity and rehydration characteristics of dried fruits and vegetables compared with conventional drying methods. Similarly, Akter *et al.* (2022) [1] highlighted the importance of mathematical modeling in understanding heat and mass transfer phenomena during drying processes and optimizing operational parameters. Recent reviews by Wu *et al.* (2022) and Boateng *et al.* (2024) [3, 32] demonstrated that the integration of emerging thermal and non-thermal technologies can substantially reduce drying time while preserving nutritional and sensory quality. Furthermore, advances in sensor-based monitoring, artificial intelligence and intelligent process control systems have enabled more precise management of drying operations, resulting in improved product uniformity and reduced energy consumption. Jimoh *et al.* (2023) and Ramachandran *et al.* (2024) [13, 24] emphasized that next-generation drying technologies are increasingly being designed to address industrial demands for sustainable processing, reduced environmental impact and enhanced product functionality. In the specific case of apple dehydration, Taghinezhad *et al.* (2023) [28] reported significant improvements in quality attributes and energy efficiency through optimized microwave drying conditions, while Wang *et al.* (2023) [30] demonstrated that advanced vacuum drying systems effectively preserve color, phenolic compounds, antioxidant activity and overall product quality. These recent developments indicate that microwave and vacuum-based drying technologies have become key research areas in modern food engineering and post-harvest processing.

Although numerous research studies have investigated microwave drying, vacuum drying and vacuum-microwave drying of apples, the available information remains scattered across various scientific publications. A comprehensive synthesis of the latest developments, drying mechanisms, quality characteristics, nutritional retention and shelf-life implications is essential for researchers, food engineers and industrial practitioners. Therefore, the present review aims to critically evaluate and summarize recent advances in

microwave and vacuum-based drying technologies for apple preservation. Particular emphasis is placed on drying principles, process kinetics, quality retention, nutritional stability, energy efficiency and shelf-life enhancement. Furthermore, current challenges, research gaps and future opportunities for industrial implementation are discussed to provide guidance for future research and technological development in sustainable fruit processing.



**Fig 1:** Structure of apple tissue and moisture migration during drying

### Microwave Drying of Apple

Microwave drying is based on volumetric heating, where electromagnetic waves interact with polar molecules, primarily water, within the food material (Metaxas and Meredith, 1983) [19]. This interaction generates heat internally, leading to rapid moisture evaporation. Numerous studies on apple slices have demonstrated that microwave drying significantly reduces drying time compared to conventional drying methods (Maskan, 2001; Zhang *et al.*, 2006) [18, 36]. Faster drying not only improves process efficiency but also reduces exposure time to heat, which can be beneficial for quality retention (Raghavan *et al.*, 2015) [22].

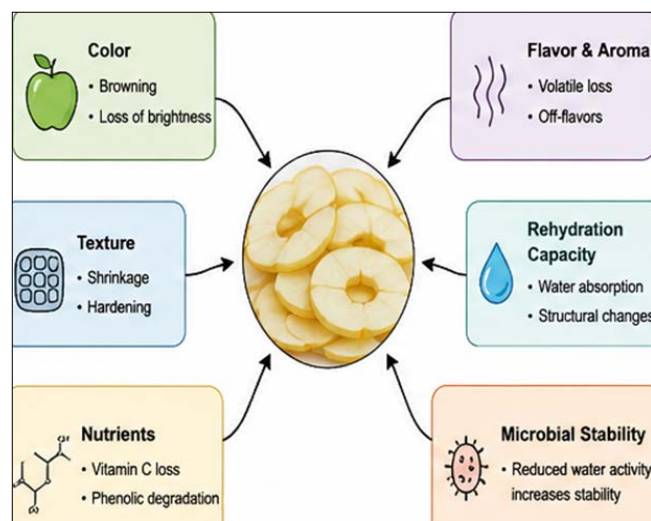
Research findings consistently indicate that microwave power level is a critical parameter influencing drying behavior. Higher power levels increase drying rate and effective moisture diffusivity due to enhanced internal heating (Doymaz and Ismail, 2011) [7]. However, several authors have also reported that excessive power can cause uneven heating, localized burning and surface scorching (Maskan, 2000; Feng *et al.*, 2012) [9, 17]. As a result, optimization of microwave power is essential to achieve uniform drying and acceptable product quality.

To address issues associated with continuous microwave drying, intermittent microwave drying has been investigated by many researchers (Gunasekaran, 1999; Zhang *et al.*, 2019) [12, 37]. In this approach, microwave energy is applied in cycles with resting periods in between. These resting periods allow temperature equalization and moisture redistribution within the apple slices. Studies have shown that intermittent microwave drying improves drying uniformity, reduces thermal damage and enhances overall product quality compared to continuous microwave application (Zhang *et al.*, 2017) [35].

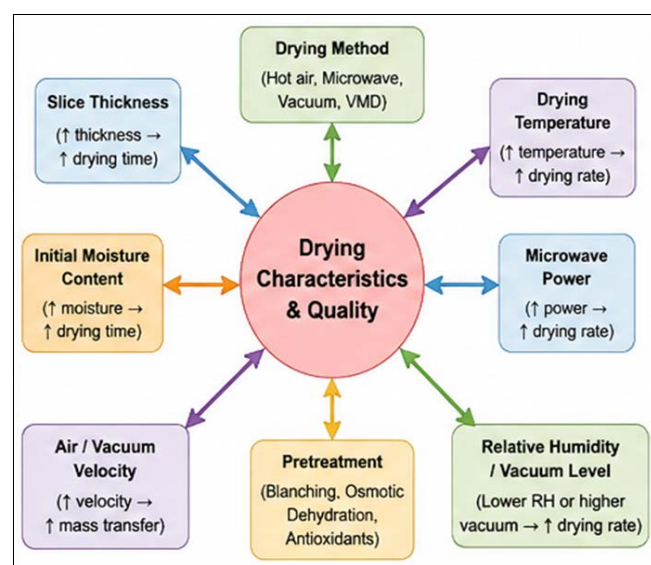
### Quality Attributes and Shelf-Life Implications of Microwave-Dried Apples

Quality evaluation of microwave-dried apples has been reported extensively in the literature. Researchers have examined physical attributes such as color, shrinkage, texture and rehydration capacity, as well as chemical properties including phenolic content and antioxidant activity (Lewicki and Jakubczyk, 2004; Vega-Gálvez *et al.*, 2012) [16, 29]. Many studies have reported that microwave drying retains higher levels of bioactive compounds than hot-air drying, mainly due to shorter drying time (Zhang *et al.*, 2006; Orsat *et al.*, 2019) [36, 37].

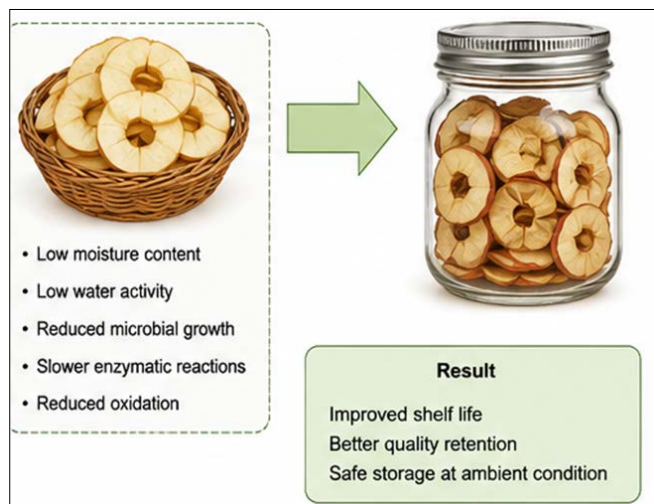
Shelf-life improvement in microwave-dried apples is primarily achieved through rapid reduction of moisture content and water activity, which restricts microbial growth and slows spoilage reactions (Rahman, 2009) [23]. However, because microwave drying is generally conducted in the presence of air, oxidative degradation of sensitive nutrients may still occur during long-term storage if packaging and storage conditions are not adequately controlled (Barbosa-Cánovas *et al.*, 2007) [2].



**Fig 2:** Quality changes occurring in apple slices during dehydration.



**Fig 3:** Major factors influencing drying characteristics and product quality of apple slices



**Fig 4:** Mechanism of shelf-life extension in dried apple products

### Vacuum and Vacuum-Microwave Drying of Apple

Vacuum drying is performed under reduced pressure, which lowers the boiling point of water and enables drying at relatively low temperatures (Mujumdar, 2014) [34]. This characteristic makes vacuum drying particularly suitable for

Heat-sensitive fruits such as apples (Ratti, 2001) [25]. Numerous research papers have shown that vacuum drying results in superior color retention and reduced enzymatic and non-enzymatic browning compared to air-based drying methods (Lewicki, 2006; Zhang *et al.*, 2017) [15, 35].

Vacuum-microwave drying combines the advantages of microwave heating and vacuum conditions. In this method, internal heating generated by microwaves accelerates moisture removal, while the vacuum environment prevents excessive temperature rise and oxidative reactions (Gunasekaran, 1999; Orsat *et al.*, 2019) [12, 21]. Several studies have reported that vacuum-microwave drying significantly shortens drying time while maintaining high product quality (Zhang *et al.*, 2019; Raghavan *et al.*, 2015) [22, 37].

Apples dried using vacuum or vacuum-microwave techniques exhibit a porous microstructure, which contributes to improved texture and higher rehydration capacity (Ratti, 2001) [25]. In addition, reduced oxygen availability during vacuum drying minimizes oxidative losses of sensitive compounds such as vitamin C and phenolic substances (Vega-Gálvez *et al.*, 2012) [29]. These factors collectively contribute to enhanced shelf-life stability of dried apple products.

**Table 1:** Summary of Key Studies on Microwave and Vacuum-Based Drying of Apples

S. No.	Author(s) and Year	Drying Method/Focus	Major Findings/Contributions
1	Maskan (2000) [17]	Microwave drying of apple slices	Demonstrated that microwave drying significantly reduced drying time compared with conventional drying methods.
2	Ratti (2001) [25]	Vacuum drying and food dehydration	Reported superior quality retention and reduced thermal damage under vacuum conditions.
3	Boyer and Liu (2004) [4]	Apple phytochemicals and health benefits	Highlighted the nutritional importance of apples and the need for preservation technologies to retain bioactive compounds.
4	Lewicki (2006) [15]	Hot-air drying of foods	Identified quality degradation issues associated with conventional drying techniques.
5	Rahman (2009) [23]	Water activity and food stability	Explained the role of moisture reduction in improving shelf-life stability of dried foods.
6	Zhang <i>et al.</i> (2014) [34]	Intermittent microwave drying	Developed drying kinetics models and reported improved rehydration characteristics of dried apples.
7	Darvishi <i>et al.</i> (2014) [5]	Microwave drying of apples	Compared intermittent and continuous microwave drying and reported improved energy efficiency.
8	Feng <i>et al.</i> (2015) [10]	Microwave drying optimization	Optimized microwave power and temperature conditions for improved drying performance and quality retention.
9	Song <i>et al.</i> (2018) [27]	Vacuum-microwave drying	Reported improved color, texture and antioxidant retention in vacuum-microwave dried apple slices.
10	Zhang <i>et al.</i> (2019) [37]	Vacuum-microwave drying technology	Demonstrated superior product quality and reduced drying time compared with conventional drying methods.
11	Wojdyło <i>et al.</i> (2021) [31]	Bioactive compounds in dried apples	Evaluated the influence of drying methods on antioxidant activity and phenolic compound retention.
12	Reis <i>et al.</i> (2022) [26]	Drying technologies for fruits and vegetables	Reviewed emerging drying technologies and emphasized quality preservation during dehydration.
13	Wu <i>et al.</i> (2022)	Advanced drying technologies	Summarized recent innovations in fruit and vegetable drying processes and quality improvement strategies.
14	Zhang <i>et al.</i> (2022) [32]	Vacuum-microwave drying review	Reported recent advances in quality retention and energy-efficient vacuum-microwave drying systems.
15	Taghinezhad <i>et al.</i> (2023) [28]	Microwave drying of apple slices	Investigated quality, energy consumption and environmental aspects of microwave drying.
16	Wang <i>et al.</i> (2023) [30]	Vacuum drying of apples	Demonstrated enhanced retention of color, texture and bioactive compounds during vacuum drying.
17	Jimoh <i>et al.</i> (2023) [13]	Recent drying technologies	Reviewed technological developments in drying systems and process optimization.
18	Ramachandran <i>et al.</i> (2024) [24]	Advanced food drying technologies	Highlighted innovations in sustainable drying processes and industrial applications.
19	Boateng (2024) [3]	Emerging thermal and non-thermal technologies	Discussed advanced drying technologies for improving quality and reducing energy consumption.
20	FAO (2024)	Global fruit production and losses	Reported increasing global fruit production and emphasized the importance of post-harvest preservation technologies.

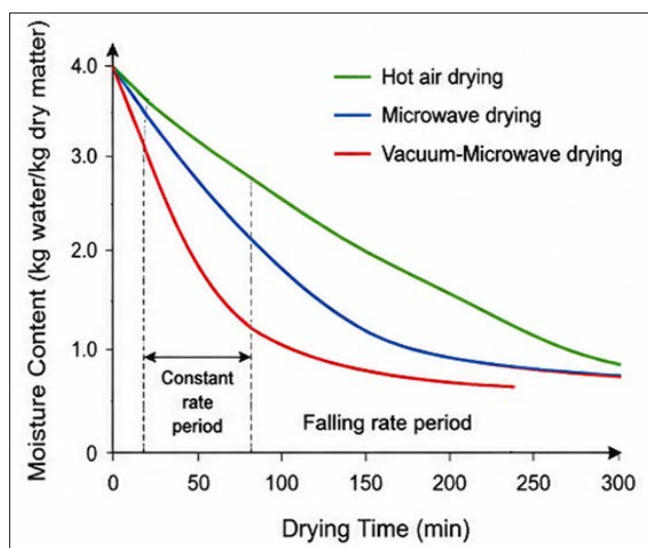
## Comparative Discussion of Microwave and Vacuum-Based Drying Methods

Comparative analysis of research findings reveals that microwave drying and vacuum-based drying methods each have distinct advantages. Microwave drying is highly efficient in terms of drying time and energy consumption, making it suitable for rapid processing applications (Maskan, 2001; Zhang *et al.*, 2006) [18, 36]. In contrast, vacuum-based drying methods are more effective in preserving quality attributes, including color, texture and nutritional value (Ratti, 2001; Lewicki, 2006) [15, 25].

Several studies have concluded that vacuum-microwave drying offers the best overall balance between drying efficiency and quality retention (Orsat *et al.*, 2019; Zhang *et al.*, 2019) [21, 37]. Shelf-life studies reported in the literature consistently show slower quality degradation in vacuum-dried apples compared to microwave-dried samples, mainly due to reduced oxidation and lower final moisture content (Rahman, 2009) [23]. The choice of drying method therefore depends on the desired balance between processing speed, product quality and economic considerations.

Parameter	Hot Air Drying	Microwave Drying	Vacuum-Microwave Drying
Drying Mechanism	Convective heat transfer	Volumetric heating (EM waves)	Volumetric heating + Low pressure
Drying Time	Long	Short	Very short
Drying Temperature	High (50–70 °C)	Moderate (40–60 °C)	Low (30–50 °C)
Energy Efficiency	Low	High	Very high
Quality Retention (Color, Nutrients, Texture)	Low	Good	Excellent
Oxidative Degradation	High	Moderate	Very low
Equipment Cost	Low	Moderate	High

**Fig 5:** Comparative evaluation of hot-air, microwave and vacuum-microwave drying methods



**Fig 2:** Typical drying kinetics of apple slices under different drying methods

## Challenges and Future Research Scope

Despite their advantages, microwave and vacuum-based drying methods face challenges related to equipment cost, process complexity and scale-up for industrial applications (Mujumdar, 2014) [20]. Uniform heating and precise control of processing parameters remain critical issues, particularly for microwave-based systems (Gunasekaran, 1999) [12]. Future research should focus on developing optimized hybrid drying strategies, integrating suitable pretreatments and conducting detailed storage studies to better understand long-term shelf-life behavior (Orsat *et al.*, 2019) [21]. Advances in modeling, sensor technology and process control may further improve drying efficiency and product quality (Zhang *et al.*, 2017) [35]. Continued research in this area will support the development of energy-efficient and high-quality apple drying technologies suitable for commercial application.

## Conclusion

This review has comprehensively discussed microwave drying and vacuum-based drying methods for the preservation of apples based on findings from multiple research papers. Microwave drying offers rapid moisture removal and improved energy efficiency, while vacuum and vacuum-microwave drying provide superior retention of physical and nutritional quality. Both methods effectively reduce water activity and extend shelf life; however, vacuum-microwave drying emerges as the most promising technique for producing high-quality dried apple products with extended storage stability. The information presented in this review provides a strong foundation for further experimental research and academic project work.

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