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Recent trends in drying technologies for retention of nutritional/functional quality of litchi: A review

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Abstract
Litchi is a popular sub-tropical fruit known for its unique aroma, flavour, and rich nutritional value. Drying is a widely used preservation method that helps reduce post-harvest losses and extend shelf life. With the growing demand for dried fruits, greater attention is needed to maintain quality standards. Since most fruits have high moisture content and are highly perishable, drying is essential to ensure year-round availability and distribution to regions where they are not cultivated. Beyond preservation, dehydration also reduces the weight and volume of the product, leading to lower costs in packaging, handling, and transportation. However, drying can affect the physical, sensory, nutritional, and microbiological properties of fruits. Conventional convective drying, while commonly used, is time-consuming and directly impacts the final product's quality. This review examines the limitations of existing litchi drying techniques and explores potential strategies to enhance the quality of dried litchi by integrating multiple drying methods.

Keywords: Litchi, drying, dehydration, preservation

Introduction

The subtropical fruit litchi (*Litchi chinensis*) is native to the South Chinese areas of Fukien and Kwangtung. It belongs to Sapindaceae family. It is referred to as the "queen of fruits" because of its exquisite flavour and remarkable look. The world's leading litchi-growing nations include Vietnam, Thailand, Malaysia, Indonesia, China and India. Together, China and India produce around 91% of the world's litchi, which is mostly sold in the surrounding areas because it is highly perishable. Litchi (*Litchi chinensis*) is a tropical fruit, which has been gaining worldwide popularity due to its distinctive flavour profile and sweet, juicy nature. Beyond its appealing taste, litchi has attracted attention for its potential health benefits. This is attributed to its rich composition of biologically active compounds, including ascorbic acid, gallic acid, and various flavonoids (Rashid *et al*., 2019) [53]. Research has indicated that these compounds may offer several therapeutic advantages, such as antioxidant, anticancer, antiaging and anti-inflammatory properties (Ma *et al*., 2016; Tan *et al*., 2020) [43, 66]. These potential health benefits have further increased interest in litchi consumption and research. However, litchi faces a significant challenge in terms of preservation. Its high moisture content makes it particularly susceptible to rapid deterioration, resulting in a relatively short shelf life. This vulnerability to spoilage emphasizes the critical need for effective preservation methods to extend the fruit's storage life and maintain its quality over longer periods (Jiang *et al*., 2018; Zhang *et al*., 2015) [37, 73]. Post- harvest losses of litchi are around 20-30% of the harvested fruit and will reach as high as 50% in future (Jiang *et al*., 2001) [33]. Using appropriate processing techniques, Litchi can be preserved for longer period, throughout the year. The shelf-life of litchi at room temperature (25 ± 2° C) is less than three days (72h). At present only about 1% of the total production is used for processing (APEDA 2021-22). The different processed products from litchi are litchi juice, squash, cordial, RTS beverage, wine, canned litchi pulp, litchi honey, dehydrated litchi pulp, frozen litchi, litchi nut. Dehydration, or drying, is widely regarded as one of the most effective methods for preserving the quality of agricultural products (Aguilera *et al*., 2003) [4]. By removing moisture from fruits, drying helps retain their nutritional value, extends their shelf life, and enhances their relative nutrient concentration. Additionally, it lowers costs associated with packaging, transportation, and handling (Ratti,

2009) [54]. Moreover, drying is a cost-effective postharvest technique that allows for better market utilization of surplus fruits. Among the various drying methods, freeze-drying is particularly effective in maintaining the color, flavour, and taste of fruits (Marques *et al.*, 2006) [28]. However, this technique requires significant energy, time, and infrastructure investment, making it a more expensive option (Wang *et al.*, 2013; Mujumdar & Law, 2010; Fan *et al.*, 2012; Jiang *et al.*, 2015a; Valadez-Carmona *et al.*, 2017) [70, 46, 22, 36, 69]. This review examines different drying technologies, focusing on optimizing the drying process for litchi while preserving its key quality attributes.

Table 1: Nutritional composition of litchi chinensis per 100 g fresh fruit

Nutrient	Value
Water	71.11-84 g
Protein	0.7-4.12 g
Lipids	0.1-3.75 g
Carbohydrates	15-89 g
Vitamin C (ascorbic acid)	15 - 36 mg
Thiamine	0.02 mg
Niacin	1.1 mg
Riboflavin	0.07 mg
Phosphorus	25 - 35 mg
Iron (mg)	0.21 - 0.7 mg
Calcium (mg)	4 - 4.90 mg
Potassium mg	140 - 180 mg
Magnesium	10.30 - 16 mg
Sodium	3.20 - 7.90 mg
Manganese	0.07 - 0.33 mg
Zinc	0.16 - 0.28 mg
Copper	0.17 - 0.23 mg

Source: Olvera *et al.*, 2025 [16]

Convective air drying

Convective air drying is a crucial unit operation in food processing, widely used to preserve highly perishable foods such as fresh fruits and vegetables (Defraeye *et al.*, 2014; Mujumdar, 2014; Jangam *et al.*, 2010) [65, 1, 31]. The drying process in fruits and vegetables is primarily diffusion-driven, where moisture moves from the interior of the product to the surface before evaporating into the surrounding air. However, the drying rate is often limited by internal resistances to water removal and surface diffusion constraints, which can affect the efficiency of moisture loss (Krokida *et al.*, 2003; Schossler *et al.*, 2012; Togrul, 2006) [39, 59, 67]. One of the most critical factors influencing the drying process is temperature, which significantly affects both the drying kinetics and the retention of essential nutrients. Studies indicate that drying at higher temperatures can lead to a considerable reduction in the nutrient content of food products (Elgamal *et al.*, 2023) [21]. when litchis are convectively dried at a temperature range of 50-70°C, their ascorbic acid content decreases from 135.9 mg/100g to 106 mg/100g dry basis. This decline is primarily due to thermal degradation, oxidative reactions, and prolonged exposure to heat and air, which accelerate the breakdown of ascorbic acid molecules. Although convective drying is effective in moisture removal, it is essential to optimize the drying conditions to minimize nutrient losses while maintaining product quality. Adjusting parameters such as drying temperature, air velocity, and pretreatments can help improve the retention of essential vitamins and antioxidants, ensuring that dried fruits remain nutritionally beneficial.

Vacuum drying

Vacuum drying is a widely used method for preserving fruits by removing moisture under reduced pressure conditions. This technique facilitates water evaporation at lower temperatures compared to conventional drying methods, which helps in preserving the nutritional quality, color, flavour, and texture of the fruits (Reis 2014; Jaya and Das 2003; Fellows 2000) [55, 32, 24]. By operating under low-temperature conditions, vacuum drying minimizes the thermal degradation of heat-sensitive bioactive compounds and nutrients, making it a highly efficient and effective drying method for fruits (Adisasmito *et al.*, 2024) [3]. A study conducted on the vacuum drying of litchis at varying temperatures within the range of 50 °C to 70 °C and an absolute pressure of 8 kPa demonstrated a reduction in the phenolic content and ascorbic acid levels. Phenolic compounds and ascorbic acid are known for their strong antioxidant properties, which contribute to the overall health benefits of fruits. Specifically, the total phenolic content declined from 834.91 mg GAE/100 g DM to 772.26 mg GAE/100 g DM, while ascorbic acid content decreased from 93.33 mg/100 g DM to 81.41 mg/100 g DM (Richter *et al.*, 2017) [56]. The observed reduction in these bioactive compounds suggests that, despite the advantages of vacuum drying in minimizing thermal degradation, some degree of nutrient loss still occurs due to exposure to elevated temperatures.

Osmotic dehydration followed by air drying

Osmotic dehydration is a promising preservation method for producing high-quality food products (Kar & Gupta, 2001; Rastogi *et al.*, 2002; Sodhi *et al.*, 2006) [38, 52, 61]. This technique involves the partial removal of moisture from fruits and other materials by immersing them in high-osmotic-pressure aqueous solutions, such as those containing sugar or salts (Pandharipande *et al.*, 2012) [49]. It is considered a crucial complementary treatment in dehydrated food processing, offering several advantages. These include minimizing heat-induced damage to flavour and color, preventing enzymatic browning, and lowering energy consumption (Sujayasree *et al.*, 2022; Alakali *et al.*, 2006; Torres *et al.*, 2012; Khan, 2012) [63, 7, 68, 51]. When combined with drying, osmotic dehydration can further enhance the shelf life of the final product by incorporating humectants that effectively reduce the fruit's water activity. In a study of litchi quarters air dried at 70°C after treating with osmotic solution of 60% sucrose and 10% salt resulted in increased moisture removal compared to 50% sucrose and 10% salt. Osmo-air dried samples had the lowest final moisture content, indicating that osmotic dehydration significantly reduced moisture content and drying time. The final products from osmo-convective drying exhibit better texture and sensory attributes (color, flavour, crispness) after storage. Sensory evaluations noted that osmo-air dried samples had higher acceptance scores compared to untreated samples, indicating improved overall quality.

Ultrasound assisted osmotic dehydration

Non-thermal preservation methods help retain the bioavailability of food components, enhance their functional and technological properties, and improve the recovery yields from agricultural products (Galanakis, 2022) [26]. Among these methods, ultrasound processing, whether applied independently or in combination with other techniques, has been found to significantly enhance food quality, making it a highly effective approach (Gong *et al*., 2022; Singla & Sit, 2021) [27, 60]. When ultrasound processing is integrated with osmotic dehydration (OD), a technique known as ultrasound-assisted OD (UAOD), it further optimizes the dehydration process by increasing mass transfer rates and improving the overall quality of the final product (Salehi *et al*., 2022) [57]. The effectiveness of UAOD results from the combined impact of osmotic pressure gradients and ultrasonic waves, which alter the fruit's cellular structure by creating microchannels, thereby accelerating moisture loss (Oladejo *et al*., 2017; Sango *et al*., 2014) [48, 58]. In a study on litchi subjected to three pretreatment conditions namely osmotic dehydration (50%) with no ultrasound (control), US 10 min + OD (50%), US 15 min +OD (50%) for 240 min. The results indicated a significant increase in both water loss (WL) and solid gain (SG) with the ultrasound-assisted treatments compared to traditional osmotic dehydration alone. Specifically, the highest levels of water loss and solid gain were achieved with the US15 + OD treatment. This was attributed to the effects of ultrasonic cavitation, which creates micropores in the cell membranes of the litchi fruits, facilitating greater permeability and thus enhancing the mass transfer during the osmotic dehydration process. Moreover, the ultrasound treatment results in a lower microbial load (2.58 ± 0.06 log CFU/g) compared to control samples (3.20± 0.05 log CFU/g) during the frozen storage period (Fong *et al*., 2021) [25].

Ultrasound assisted Hot air drying

Ultrasound assisted hot air drying (UAHAD) is an innovative dehydration technique that integrates ultrasonic energy into conventional hot air-drying processes to enhance efficiency and product quality (Liu *et al*., 2014; Nowacka *et al*., 2022) [42, 47]. Traditional hot air drying, while widely used for food preservation, often suffers from drawbacks such as prolonged drying times, high energy consumption, and potential degradation of heat-sensitive nutrients and sensory attributes (Calin *et al*., 2020; Wang *et al*., 2018; Stamenkovic *et al*., 2019) [12, 71, 62]. The incorporation of ultrasound aims to address these limitations by accelerating moisture removal and improving the overall drying performance. In a study on litchi drying, three treatment conditions were applied: a non-ultrasound treatment (control), an ultrasound treatment with distilled water for 10 min (UT-1), and an ultrasound treatment with ice water (UT-2). The control group experienced a total drying time of approximately 8.5 hours, while both ultrasonic treatment groups significantly reduced drying time to about 4.0 to 4.5 hours. In the UT-1 treatment, which utilized distilled water, the litchi fruits retained around 70% to 75% of their vitamin C and about 60% to 70% of total phenolic content, showcasing the method effectiveness in preserving nutrients. The application of ultrasound also aided in maintaining the levels of sugars, enhancing the fruits flavour. In contrast, the UT-2 treatment, which incorporated ice water to prevent excessive heating, demonstrated a further beneficial effect by allowing the fruits to retain similar nutrient levels (Cao *et al*., 2020) [13]. As a result, both ultrasound-assisted methods proved more effective than the traditional drying technique, enhancing the overall quality and shelf life of dried litchi fruits while promoting nutrient retention.

Intermittent ohmic heating: Ohmic heating is an advanced thermal processing technique that utilizes electrical resistance to generate heat within food products. This method ensures rapid, uniform heating while minimizing thermal degradation, making it particularly beneficial for heat-sensitive foods such as fruits (Kumar 2018; Zell *et al*., 2009; Alkanan *et al*., 2021; Zhong *et al*., 2003; Zhu *et al*., 2010) [40, 72, 8, 74, 75]. Intermittent ohmic heating (IOH) is a modified approach where electrical heating is applied in cycles rather than continuously. This technique allows for better control over temperature profiles, reducing excessive thermal stress and preserving the sensory and nutritional qualities of fruits (Cao *et al*., 2020) [13]. IOH also enhances energy efficiency and can improve the texture, color, and bioactive compound retention in processed fruits. In a study on intermittent ohmic heating (IOH) of litchi, its effects on quality were compared to those of continuous ohmic heating (COH). Using a $BaTiO_3$-resistance attached to the heater element, IOH operates in cycles (20 min on, 5-15 min off) at 70°C with 1.8 m/s air velocity. This method reduces energy consumption (341-427 $kJ \cdot g^{-1}$) compared to COH, lowering costs and minimizing thermal degradation. IOH preserves more vitamin C (50%) and phenolic compounds (70%) than COH, which preserves 40% and 50%, respectively (Cao *et al* 2020) [13]. It also maintains color, reduces browning, improves texture, and enhances flavour by limiting off-flavours. Overall, IOH offers superior nutritional and sensory benefits with greater energy efficiency.

Intermittent microwave vacuum drying

Microwave vacuum drying is an innovative food dehydration technique that integrates microwave radiation into a conventional vacuum drying system. Instead of relying on conduction and convection for heat transfer, this method utilizes microwave energy to heat and evaporate moisture. By combining the benefits of rapid volumetric heating through microwaves with low-temperature moisture evaporation under vacuum, this approach significantly accelerates the drying process. As a result, it requires less time to achieve complete drying compared to traditional methods (Drouzas & Schubert, 1996; Durance & Wang, 2002; Erle & Schubert, 2001; Sutar & Prasad, 2011) [18, 19, 20, 64]. In a study on Intermittent Microwave Vacuum Drying (IMVD), it was found to be a more energy-efficient method for drying litchi, consuming 31% less energy (32-45 kJ/g) compared to Continuous Microwave Vacuum Drying (CMVD), which requires 65.7 kJ/g when dried at 70°C, 0.05 MPa at 2W/g. IMVD better preserves nutrients, retaining 60% of Vitamin C compared to CMVD's 30-50%, and maintains 70-75% of total phenolic compounds, enhancing antioxidant properties. It also reduces browning, achieving a higher lightness (L*) value (29.44-25.71) than CMVD (22.62). Sugar retention is superior in IMVD, with glucose and fructose levels of 28.62 g/100 g and 23.17 g/100 g, respectively, compared to 25.11 g/100 g and 18.68 g/100 g in CMVD. Sensory evaluation confirms IMVD's superiority in color, taste, and texture, scoring 4.34/5 compared to CMVD's 3.64/5 (Cao *et al*., 2019) [15]. Thus, IMVD is the preferred method for drying litchi, preserving nutrients, minimizing browning, enhancing sensory appeal, and retaining more sugar.

Freeze vacuum drying combined with heat pump drying

Freeze vacuum drying (FD), also known as lyophilization, is a drying technique that removes moisture through sublimation. This method is recognized for its superior ability to preserve the quality of fruits and vegetables compared to other drying techniques (Abbasi & Azari, 2009; Argyropoulos *et al*., 2011; Huang & Zhang, 2015; Monteiro *et al*., 2016) [2, 5, 73, 45]. Freeze-dried foods are characterized by high porosity, minimal degradation of color, flavour, and nutrients, as well as excellent rehydration ability (Jiang *et al*., 2014a; Jiang *et al*., 2017) [34, 35]. Heat pump drying (HPD) is another low-temperature drying method that is energy-efficient and functions effectively even in humid conditions (Ansari *et al*., 2024) [10]. One of the key advantages of HPD is its ability to retain product quality, making it particularly suitable for drying heat-sensitive fruits and vegetables. This technique not only improves the final product's quality but also reduces energy consumption (Fayose & Huan, 2016) [23]. The combination of freeze vacuum drying with heat pump drying (FH) offers significant advantages in the production of litchi pulp (An *et al*., 2022) [9]. This innovative two-step drying process enhances efficiency by reducing the overall drying time by approximately 50% compared to traditional freeze-drying methods. Additionally, it is highly energy-efficient, consuming only about 20% of the energy required by conventional drying techniques. Moreover, the FH method enhances the content of beneficial components in litchi pulp, resulting in higher levels of neutral sugars (57.05%), proteins (6.35%), and uronic acids (34.53%). It also improves the microstructure quality of litchi pulp by minimizing thermal aggregation, leading to a more uniform distribution. As a result, litchi pulp produced through this method exhibits superior biological activities, including enhanced antioxidant capacity and improved hypoglycemic effects. These attributes position FH as an efficient and high-quality alternative for industrial applications in litchi pulp production.

Conclusion

Litchi (*Litchi chinensis*) is a highly perishable fruit with considerable nutritional and economic value, necessitating the application of effective drying technologies to enhance its shelf life while maintaining its essential quality attributes. This review explored various drying methods, including convective air drying, vacuum drying, osmotic dehydration, ultrasound-assisted drying, intermittent ohmic heating, and intermittent microwave vacuum drying, each with distinct advantages and limitations concerning drying kinetics, energy efficiency, nutrient retention, and sensory attributes. Among the studied techniques, ultrasound-assisted drying, intermittent microwave vacuum drying and freeze vacuum drying combined with heat pump drying have emerged as promising approaches due to their ability to improve drying efficiency while preserving bioactive compounds, color, and flavour. These methods facilitate rapid moisture removal with minimal thermal degradation, making them suitable for retaining litchi's functional properties. In contrast, freeze-drying, while highly effective in maintaining fruit quality, remains cost-prohibitive and energy-intensive, restricting its large-scale application. The integration of non-thermal techniques, such as ultrasound and osmotic dehydration, further enhances drying performance by reducing processing time and mitigating nutrient losses, thereby improving the overall efficiency of the drying process. Despite advancements in drying technologies, challenges remain in optimizing process parameters to balance drying efficiency, product quality, and energy consumption. Future research should focus on the development of hybrid drying systems that combine multiple technologies to maximize nutrient retention and minimize processing time. Additionally, exploring novel pre-treatment strategies, such as enzymatic treatments or bio-based coatings, may further enhance the effectiveness of drying methods while preserving the fruit's physicochemical properties. Advancements in mathematical modeling and computational simulation can also aid in predicting drying behaviour, optimizing energy use, and improving process control. Expanding the commercial adoption of these advanced drying techniques is essential for reducing post-harvest losses, ensuring product consistency, and enhancing the economic viability of litchi processing.

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