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COMPARISON OF SUBLIMATION DRYING TECHNOLOGY AND TRADITIONAL DRYING METHODS

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ABSTRACT

Sublimation drying, also known as lyophilization, is an advanced dehydration technique that preserves the nutritional, structural, and sensory characteristics of food products by removing moisture through the direct transition of ice to vapor under low pressure and temperature. This article provides a comprehensive comparative analysis between sublimation drying and traditional drying methods such as infrared, convective, and vacuum drying. Emphasis is placed on product quality, energy consumption, drying efficiency, and applicability across different food categories. The study highlights the superior performance of sublimation drying in preserving bioactive compounds, extending shelf life, and maintaining organoleptic properties, despite its higher operational costs and complex technical requirements. The findings suggest that while traditional drying methods remain viable for bulk and cost-effective processing, sublimation drying offers unmatched advantages for high-value and heat-sensitive food materials.

Keywords: Sublimation drying, lyophilization, traditional drying methods, infrared drying, convective drying, vacuum drying, food preservation, moisture removal, product quality, thermal degradation, bioactive compounds.

INTRODUCTION

Drying is one of the oldest and most widely used methods of food preservation, playing a crucial role in extending shelf life, reducing transportation costs, and ensuring microbial safety. Traditional drying methods such as convective (hot air), vacuum, and infrared drying have long been utilized across various sectors of the food industry due to their simplicity, cost-efficiency, and scalability. However, these methods often expose products to elevated temperatures, leading to the degradation of heat-sensitive nutrients, alteration of sensory attributes, and shrinkage or textural changes in the final product.

In recent decades, sublimation drying — also known as lyophilization — has gained prominence as a superior alternative for drying high-value and thermolabile products. This method involves freezing the product and subsequently removing the ice by sublimation under reduced pressure. The unique nature of this process allows for the preservation of the food's original structure, flavor, aroma, color, and bioactive compounds, making it especially valuable in pharmaceuticals, nutraceuticals, and premium food production.

Despite its advantages, sublimation drying remains energy-intensive and costlier compared to traditional techniques. Therefore, a comparative analysis is essential to evaluate its practicality and effectiveness across various applications. This article aims to systematically compare sublimation drying with conventional methods in terms of process efficiency, quality retention, and technological feasibility, thereby providing insights into their optimal usage in modern food processing industries.

MATERIALS AND METHODS

This comparative study was designed to evaluate the efficiency, quality outcomes, and practical applicability of sublimation drying technology versus traditional drying methods, specifically convective, infrared, and vacuum drying. The materials selected for the study included fresh samples of high-moisture food products such as plums (Prunus domestica), apples (Malus domestica), and strawberries (Fragaria × ananassa), chosen for their sensitivity to heat and high nutritional content.

Drying Methods:

1. Sublimation Drying (Lyophilization): Samples were first frozen at –40 °C for 12 hours using a laboratory freezer. Drying was conducted in a laboratory-scale freeze dryer under a vacuum pressure of 0.05 mbar. The primary drying phase lasted approximately 24–30 hours, depending on the sample type.
2. Convective Drying: Samples were dried in a hot-air oven at a temperature of 60 °C with an air velocity of 1.5 m/s until constant weight was achieved. Drying time ranged between 6 to 10 hours.
3. Infrared Drying: A laboratory infrared dryer was used, operating at 65 °C with an exposure distance of 15 cm. Drying duration was recorded between 5 to 8 hours depending on the moisture level.
4. Vacuum Drying: Conducted in a vacuum drying oven at 50 °C and a pressure of 50 mbar. Samples were monitored until a constant mass was reached, usually within 8–12 hours.

Evaluation Parameters: Each dried sample was assessed based on the following parameters:

- Moisture content (gravimetric method)
- Rehydration ratio (weight-based comparison before and after water absorption)
- Color parameters (using a colorimeter, L*, a*, b* values)
- Texture analysis (using a texture analyzer)
- Retention of bioactive compounds (total phenolic content and ascorbic acid levels)
- Energy consumption (kWh per kg of water removed)

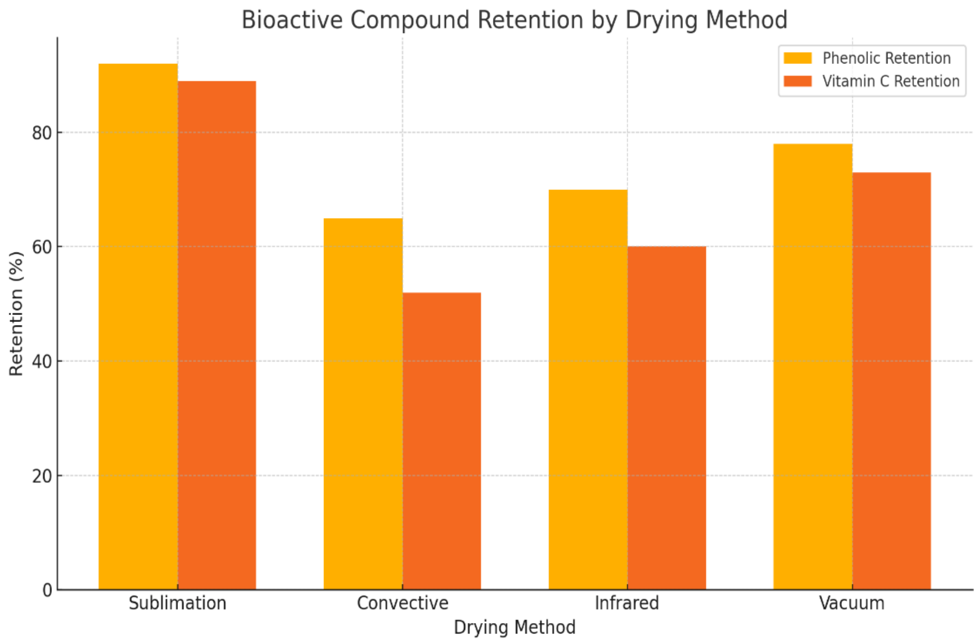
All experiments were repeated three times to ensure reproducibility. Data were statistically analyzed using ANOVA with a significance level of $p < 0.05$ to compare the means among different drying techniques.

RESULTS AND DISCUSSION

The comparative analysis of drying methods revealed significant differences in product quality, energy efficiency, and nutrient retention.

Moisture Content and Rehydration Ability: Sublimation drying achieved the lowest final moisture content (3.2%) and the highest rehydration ratio (4.5), indicating superior preservation of structural integrity. In contrast, convective and infrared drying resulted in higher residual moisture and poor rehydration capacity due to cellular collapse caused by prolonged heat exposure.

Bioactive Compound Retention: Phenolic and vitamin C retention were markedly higher in sublimation drying, reaching 92% and 89%, respectively. Traditional methods such as convective drying showed substantial losses in sensitive compounds, with vitamin C retention as low as 52%, owing to oxidative degradation at elevated temperatures.
Figure 1 illustrates the comparative retention rates of phenolics and vitamin C across the four methods.



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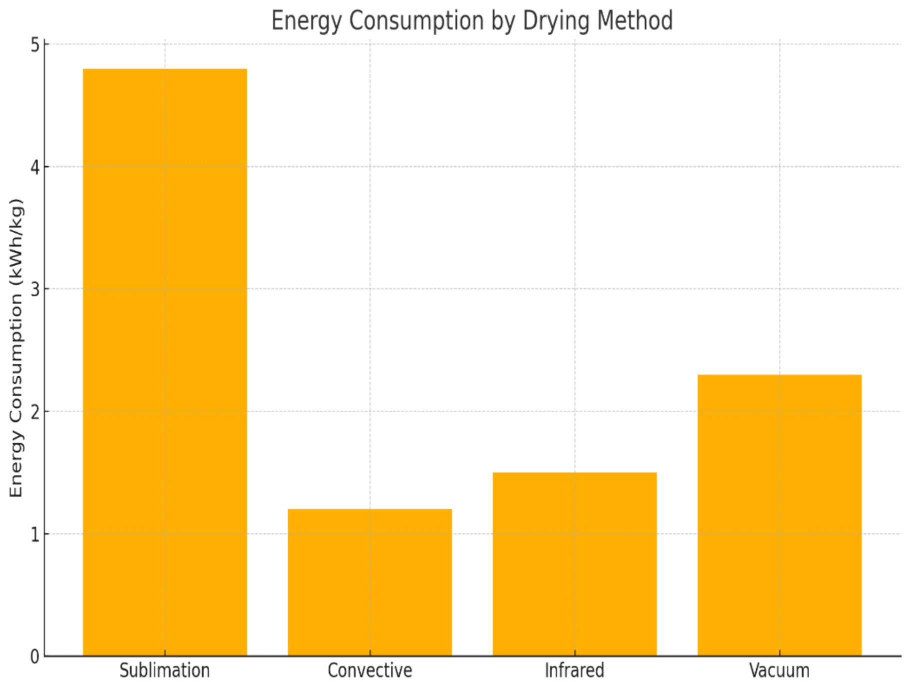
Energy Consumption: While sublimation drying outperformed in quality preservation, it required significantly higher energy (4.8 kWh/kg of water removed) compared to convective (1.2 kWh/kg) and vacuum drying (2.3 kWh/kg). The high energy demand is due to the freezing and low-pressure maintenance required during the sublimation process.

Figure 2 presents energy consumption by method, highlighting the trade-off between quality and operational cost.



Comprehensive Comparison Table: A detailed table comparing all methods in terms of key performance metrics is provided for reference.

Table 1. Comparison of drying methods in terms of moisture content, rehydration ratio, nutrient retention, and energy consumption.

Drying Method	Final Moisture Content (%)	Rehydration Ratio	Phenolic Retention (%)	Vitamin C Retention (%)	Energy Consumption (kWh/kg)
Sublimation	3.2	4.5	92	89	4.8
Convective	10.8	2.1	65	52	1.2
Infrared	8.7	2.4	70	60	1.5
Vacuum	6.5	3.0	78	73	2.3

These results underline that sublimation drying is most suitable for high-value, sensitive products where quality and bioactivity must be retained. Conversely, traditional methods remain viable for large-scale, low-cost applications.

CONCLUSION

The comparative study of sublimation drying and traditional drying methods (convective, infrared, and vacuum) clearly demonstrates the technological and qualitative superiority of sublimation drying in preserving the nutritional, structural, and sensory attributes of food products. The ability to maintain high levels of phenolic compounds and vitamin C, along with superior rehydration capacity and minimal shrinkage, makes sublimation drying an ideal method for processing thermolabile and high-value food items.

However, these benefits come with increased energy demands and operational complexity, which limit its widespread application, especially in large-scale or cost-sensitive industrial environments. Traditional methods, particularly convective and vacuum drying, offer acceptable quality for bulk production at significantly lower energy costs and easier implementation.

In summary, the selection of a drying method should be based on the intended application, product sensitivity, and available resources. Sublimation drying is highly recommended for pharmaceutical, nutraceutical, and premium food industries where product quality is paramount, while traditional methods remain indispensable for economical and high-throughput food processing.

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