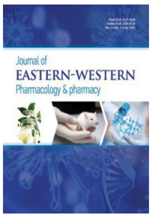

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A review of drying technologies for the production of powdered sea buckthorn *(Hippophae Rhamnoides* L.*)* Juice

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ABSTRACT: Sea buckthorn (*Hippophae rhamnoides* L.) is a nutrient-dense berry rich in vitamin C, flavonoids, and polyphenolic compounds; however, its pulp, containing approximately 80–90% moisture, is highly perishable and prone to rapid deterioration without appropriate preservation. The conversion of sea buckthorn juice into a dry powder represents an effective strategy to extend shelf life, reduce transportation and storage costs, and produce a stable ingredient suitable for applications in the food, nutraceutical, and cosmetic industries. This review provides a comprehensive overview of drying technologies applied to sea buckthorn juice, encompassing both conventional methods (natural sun and shade drying, hot-air drying) and advanced techniques, including heat-pump drying, infrared drying, spray drying, pulsed-vacuum drying, freeze-drying, and hybrid drying approaches. The operating principles, drying kinetics, and effects of each method on critical quality attributes—such as color stability, vitamin C retention, total phenolic content, and sensory properties—are systematically compared. Freeze-drying consistently demonstrates superior preservation of bioactive compounds, often yielding phenolic contents 1.5–3 times higher than those obtained by alternative drying methods; however, its industrial application is constrained by high energy consumption and prolonged processing times. Spray drying offers advantages in terms of rapid processing and scalability, although the elevated inlet temperatures (150–220 °C) may lead to significant degradation of thermolabile constituents. Pulsed-vacuum drying has emerged as a promising alternative, achieving nutrient retention comparable to freeze-drying while substantially reducing processing costs. Furthermore, hybrid drying strategies, such as infrared-assisted hot-air drying, have been shown to significantly shorten drying time and enhance the retention of bioactive compounds. Based on the reviewed literature, this paper highlights the importance of optimizing carrier agents, pretreatment strategies, and combined drying techniques to improve process efficiency and ensure high-quality sea buckthorn juice powders suitable for industrial applications.

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INTRODUCTION

Sea buckthorn (*Hippophae rhamnoides* L.) is a hardy, drought-resistant plant that thrives in harsh climates, making it well-suited to the temperate and arid regions of Central and East Asia. Globally, approximately 1.5 million hectares of land are devoted to sea buckthorn cultivation, with nearly 90% located in China. In Mongolia, the plant is widely distributed across 13,500 hectares, where it plays an important ecological and economic role. In recent years, there has been a significant increase in global interest in plant-based and natural products, which has driven up demand for sea buckthorn and its derived products[1].

Sea buckthorn is a hardy deciduous shrub whose bright orange berries are rich in vitamins (especially C), flavonoids (quercetin, kaempferol, isorhamnetin), phenolic acids, and other bioactives. These compounds confer antioxidant, anti-inflammatory, and cardioprotective effects, making sea buckthorn important in food, nutraceutical, and cosmetic industries. Fresh berries also supply β-carotene and essential fatty acids. However, the berries' pulp is very moist (80–90% water) and has a fragile skin. Left at ambient conditions, the pulp ferments and spoils within hours. As a result, fresh sea buckthorn has a short shelf life and high spoilage risk unless rapidly preserved. Common short-term preservation methods include freezing or processing into juice, but freezing can degrade nutrients over time, and liquid juices are bulky and prone to oxidation[2].

Drying is an effective way to stabilize sea buckthorn by removing water while retaining nutritional value. Converting sea buckthorn juice into a powder prolongs shelf life, reduces transportation and storage costs, and broadens applications (e.g. instant beverages, supplements, food colorants). Encapsulated juice powders can also protect sensitive compounds and improve ease of use in products. However, the drying process must balance speed, energy use, and preservation of heat-labile nutrients. In general, spray drying and freeze-drying are the most common methods for juice powders: spray drying is rapid and cost-effective, whereas freeze-drying, being a low-temperature vacuum process, better retains color and vitamins[3].

MATERIALS AND METHODS

This review was conducted based on a structured literature search using international scientific databases. Peer-reviewed publications related to drying technologies applied to sea buckthorn (*Hippophae rhamnoides* L.) were identified through keyword searches in PubMed, Google Scholar, and Frontiers, using terms such as "Hippophae rhamnoides," "sea buckthorn," and "drying process." Studies were screened based on relevance, language, and availability of full-text articles, focusing on publications from 2011 to 2024. A total of 81 records were initially identified through database searches. After removal of duplicates and screening of titles and abstracts, 37 full-text articles were assessed for eligibility, and finally, 24 studies were included in the qualitative synthesis. Extracted data were used to compare the efficiency, advantages, and limitations of various drying techniques.

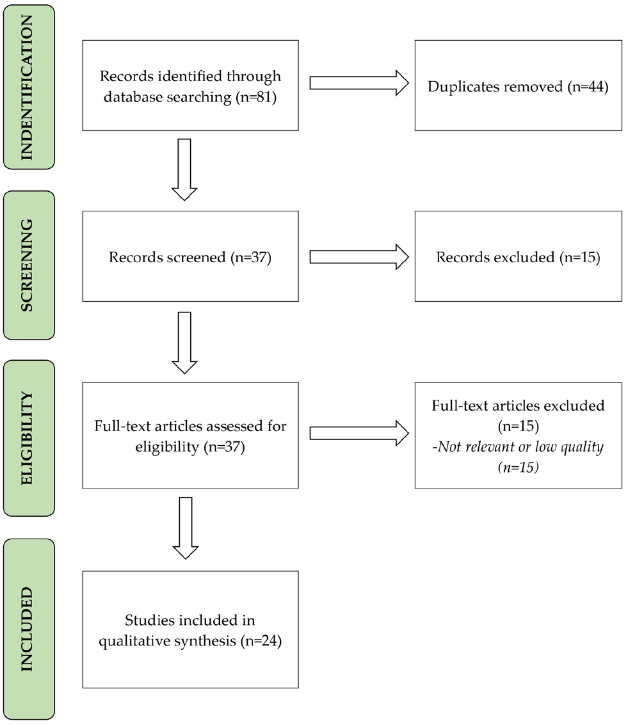

Figure 1. *PRISMA flow diagram of the literature selection process.*

1. Progress of Sea Buckthorn Drying Technology

The drying process fundamentally involves the evaporation of water from within the material via a migration pathway toward the exterior.[5]

1.1. Vacuum Freeze-Drying

In recent years, vacuum freeze-drying has emerged as an advanced and effective technology for preserving sea buckthorn. This method capitalizes on the phase transitions of water and typically consists of three main stages:[6]

Pre-Freezing Stage The sea buckthorn material is cooled below its eutectic temperature, which converts the internal free water from liquid to solid form. This step is crucial for preserving the structural integrity of the material during subsequent drying.

Primary (Sublimation) Drying Stage Under low-pressure vacuum conditions, the ice formed during pre-freezing undergoes sublimation—transitioning directly from a solid to vapor—without passing through the liquid phase. This step is responsible for removing the majority of the moisture.

Secondary (Desorption) Drying Stage
In this final phase, bound water molecules—those associated with cell walls and internal structures—are removed through gradual heating, completing the drying process and reducing residual moisture content to a stable level.

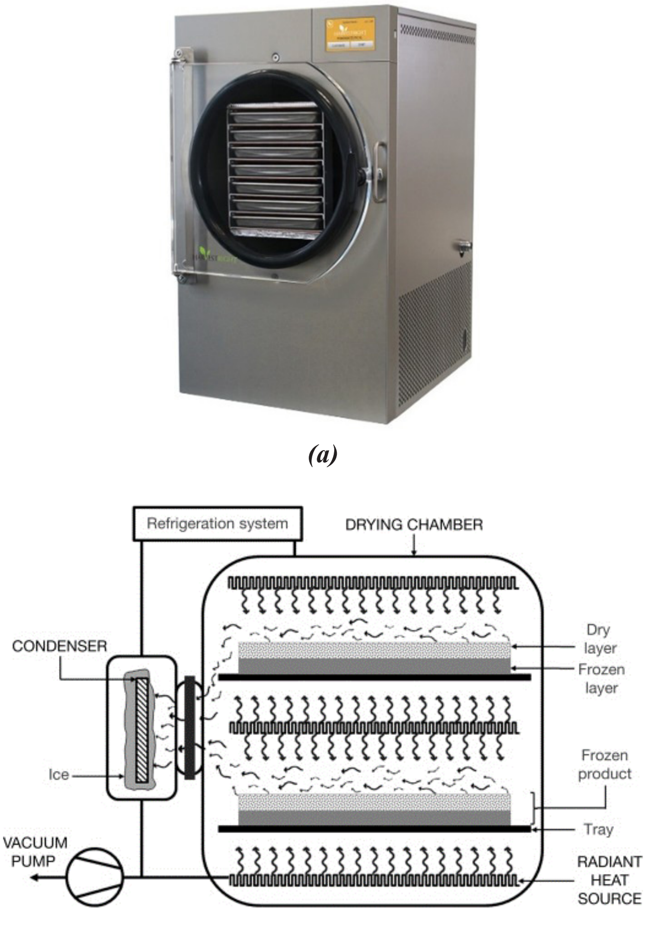

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Figure 2. *a. Batch of a freeze dryer, b. Element of a freeze dryer*[5]

Vacuum freeze-drying (lyophilization) involves three steps: freezing the material, sublimating the ice under vacuum, then desorbing bound water. This low-temperature process maximally preserves heat-sensitive compounds. Research on sea buckthorn has shown that freeze-drying produces superior nutritional quality: Li et al. reported that total phenolic content in freeze-dried berries was 1.6–2.97 times higher than in air-dried counterparts, and flavonoid retention was also highest. Gutierrez et al. found that oil extracted from freeze-dried sea buckthorn pulp had a much lower peroxide value (oxidative marker) than from hot-air dried pulp, indicating better oil quality[7].

While the powder quality is excellent (bright color, intact microstructure, rich bioactives), freeze-drying has drawbacks. It requires expensive equipment and is very energy-intensive because no convective heat is used. Heat and mass transfer in vacuum are slow, so drying cycles can take 24+ hours for berries. Consequently, vacuum freeze-drying is often impractical for large-scale processing. Future work aims to shorten freeze-drying time via optimized pretreatments and by using sensors or control algorithms to precisely determine the end-point[8].

1.2. Spray Drying

Spray drying is a common industrial method to turn liquid products into powder. The juice is atomized into fine droplets and exposed to a hot air stream, instantly evaporating moisture. Compared to liquid juice, the resulting powder is more stable and easier to store. The process is very quick and can be easily scaled up. In the context of sea buckthorn, spray drying is typically used either for making beverage powders or microencapsulating sea buckthorn oils. Process optimization studies have found that inlet air temperature and carrier content are critical variables: for example, one study using response-surface methods found optimal drying at ~162°C inlet and ~25% maltodextrin, balancing low moisture with good vitamin C and color retention[9].

The downside of spray drying is heat stress. Inlet temperatures of 150–220 °C can degrade vitamin C and sensitive compounds. Energy use is high, and fruit juices tend to stick to equipment walls. To counteract stickiness (low glass-transition of sugars and acids), carriers like maltodextrin or inulin are commonly added. In fact, sea buckthorn juice powders with inulin exhibited better water-holding capacity than with maltodextrin. Thus, spray drying of sea buckthorn juice typically involves adding 10–30% carrier to produce free-flowing, non-hygroscopic powders. Overall, spray drying yields fine, uniform powder efficiently, but requires careful formulation to protect quality[10].

- **Juice Powder Production**
  Selvamuthukumaran et al. 11 applied response surface methodology (RSM) to optimize the spray-drying conditions for sea buckthorn pulp beverages. Key quality indicators such as moisture content, solubility, dispersibility, vitamin C retention, and color difference were modeled. Their optimized conditions involved an inlet air temperature of 162.5 °C and the addition of 25% maltodextrin (w/w) as a carrier agent.

- **Oil Microencapsulation**
  In another study, Čulina et al.12 investigated the encapsulation of sea buckthorn pulp oil via spray drying. They reported that increasing the inlet air temperature enhanced powder yield, solubility, and encapsulation efficiency. However, higher temperatures negatively impacted moisture content, total carotenoids, and antioxidant properties. Optimal results were achieved at an inlet temperature of 120 °C using β-cyclodextrin as the encapsulating agent with a core-to-wall ratio of 1:4.

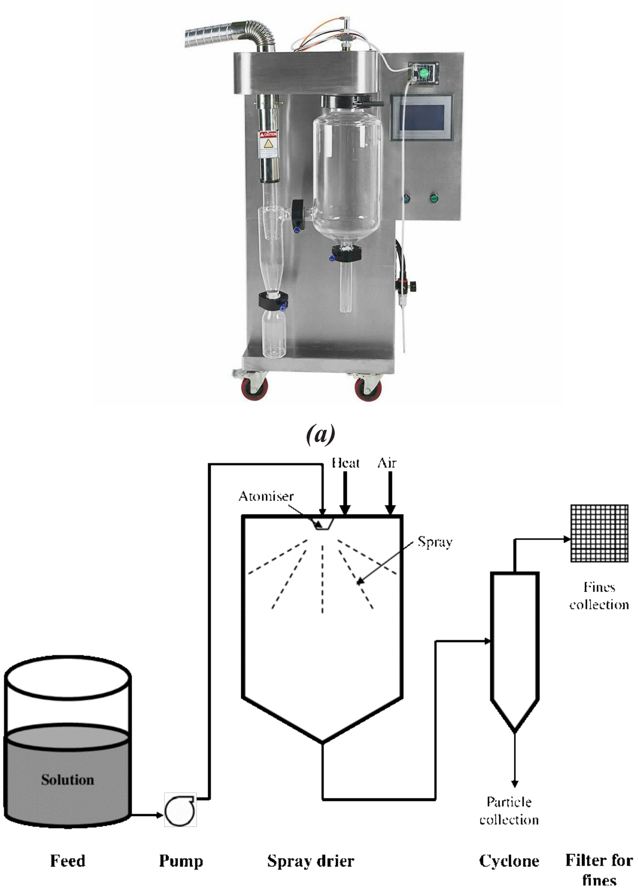

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Figure 3. *a. Batch of a spray dryer,*
b. Element of a spray dryer[12]

Despite its benefits, spray drying presents some challenges. High inlet temperatures (typically 150–220 °C) can lead to thermal degradation of heat-sensitive compounds such as vitamin C13. Additionally, the process requires substantial energy, involves large-scale equipment, and may encounter operational issues like wall deposition (stickiness) during drying.

1.3 Pulsed Vacuum Drying

Vacuum drying is a low-pressure thermal dehydration technique in which the material is either heated under vacuum to lower its boiling point or pre-frozen and then dried in the absence of air. Operating in a sealed environment, this method minimizes oxidative degradation by isolating the material from atmospheric oxygen, thus maintaining product quality more effectively than conventional drying methods.[14,15]

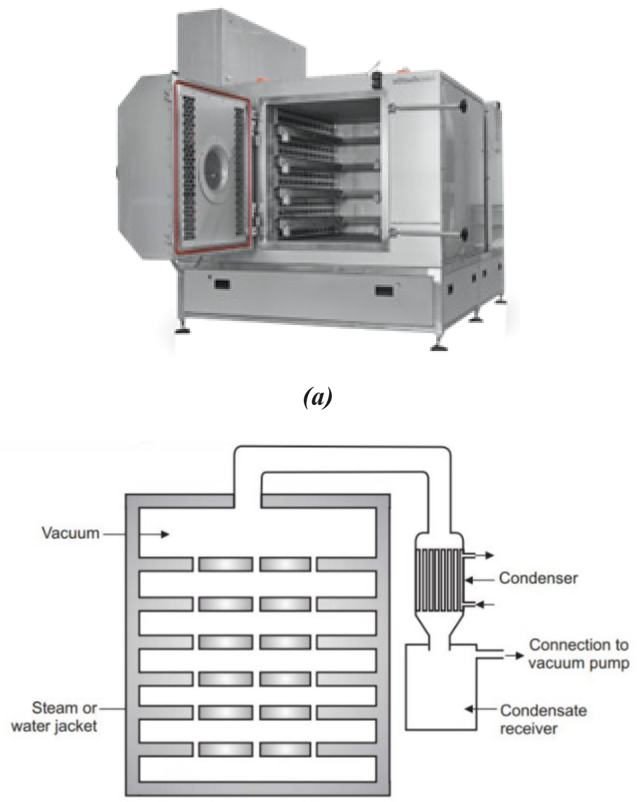

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Figure 4. *a. Batch of a pulsed vacuum dryer,*
b. Element of a pulsed vacuum dryer[16]

A more advanced variation, known as pulsed vacuum drying (PVD), enhances the efficiency of traditional vacuum drying by cyclically alternating between vacuum and atmospheric pressure. This pulsing mechanism creates compressive and expansive forces within the microstructure of the material, forming micro-channels that significantly improve internal moisture migration and diffusion rates[16].

Studies of PVD on sea buckthorn show promising results. Araya-Farias et al. reported that vacuum drying (50 °C) was about 43% slower than HAD, but it increased retention of total phenolics and vitamin C (by ~24.4 mg and 2.24 mg per 100 g, respectively) compared to HAD. Geng et al. compared PVD to other methods and found that both PVD and freeze-drying preserved the highest ascorbic acid and phenolic levels, as well as excellent rehydration and color. Notably, PVD achieved quality close to freeze-drying at much lower cost. However, the drying rate of pure PVD can be slow; thus it is often combined with other heating (microwaves or IR) to shorten process time. In summary, PVD of sea buckthorn juice yields powders with very high nutrient retention and minimal browning, making it an attractive industrial option when energy/time can be allowed[17].

1.4. Infrared-Radiation drying

Infrared (IR) radiation drying is considered a modern and eco-friendly dehydration method that offers notable advantages, including uniform heating, strong penetration capability, high heat transfer efficiency, and relatively rapid moisture removal. The fundamental principle behind this technique lies in the interaction between infrared waves and the material's surface molecules. Upon irradiation, inorganic and organic macromolecules absorb the energy, begin to vibrate, and generate internal frictional heat, which facilitates the removal of moisture.[18]

In the context of sea buckthorn drying, IR drying has been explored both in terms of optimizing drying parameters and understanding its effects on energy consumption. For example, Geng et al.[19] compared various drying methods and reported that IR drying at 300 W and 60 °C provided a faster initial drying rate compared to conventional hot-air drying (60 °C, 2.2 m/s). However, the total drying time was longer, likely due to structural changes within the fruit caused by deep heat penetration. These changes negatively affected the rehydration capacity of dried sea buckthorn, as the inner cellular structure was disrupted. Similar microstructural alterations, such as a smoother surface with occasional pores, were confirmed through epidermal analysis in studies by Zhang et al. and Huang et al.[20,21]

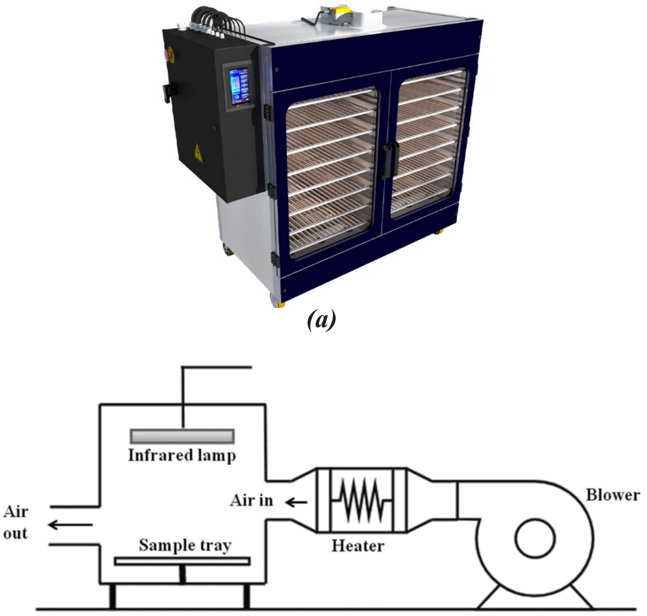

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Figure 5. *a. Batch of a infrared-radiation drying, b. Element of a infrared-radiation drying*[20]

Despite its ability to retain higher levels of total flavonoids, phenolic compounds, and ascorbic acid compared to hot-air and infrared-assisted hot-air drying, IR drying does not outperform advanced methods like vacuum freeze-drying or pulsed vacuum drying in terms of color preservation and structural integrity. Specifically, infrared-dried samples show lower ΔE (color difference) and browning index values but still fall short in brightness (L*) and rehydration potential.

Therefore, while IR drying holds promise due to its efficiency and nutrient preservation, its strong penetration and localized overheating tendencies can cause significant thermal damage, making it less suitable for use in the pre-drying stage of delicate fruits like sea buckthorn. Future research should focus on integrating IR drying with other gentle drying techniques to balance drying kinetics, product quality, and energy efficiency, thereby achieving optimized outcomes for sea buckthorn processing.[22]

1.5. Heat pump drying

Heat naturally flows from regions of higher temperature to those with lower temperature. However, a heat pump system defies this natural direction by utilizing external energy to transfer thermal energy from a low-temperature source to a higher-temperature environment. As the amount of usable heat output typically surpasses the energy input required for operation, heat pump drying is regarded as an energy-efficient and environmentally friendly technique.[23]

Compared to conventional drying methods, heat pump drying offers several advantages: improved energy efficiency, lower operating costs, better retention of product quality, and reduced environmental impact. Although it is a relatively new innovation in the context of sea buckthorn processing, it shows great promise.

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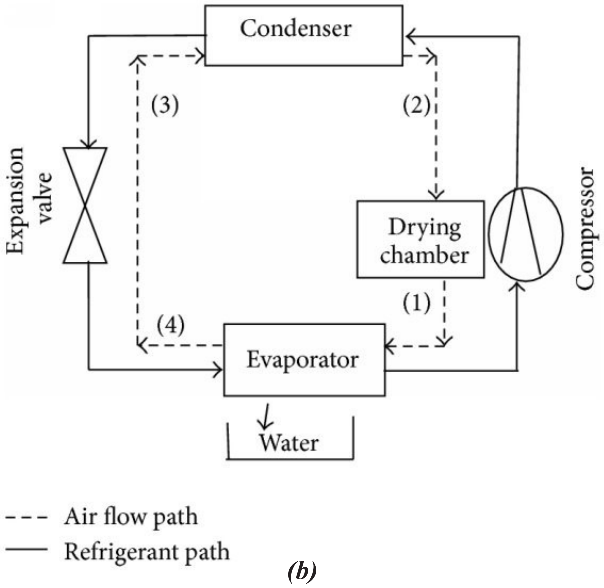

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Figure 6. *a. Batch of a heat pump drying, b. Element of a heat pump drying*[23]

Despite its advantages, current heat pump systems are generally limited to low-temperature drying, which results in longer drying durations. Additionally, the equipment investment is relatively high, which may restrict its immediate large-scale application. Future studies should focus on optimizing the energy consumption and refining the drying process parameters to better adapt heat pump technology to sea buckthorn drying. As a refinement of traditional hot-air drying, heat pump drying holds strong potential for industrial-scale use in producing high-quality dried sea buckthorn products.[24]

Table 1. Comparison of Drying Techniques for Sea Buckthorn

Drying Method	Drying Temperature Range	Drying Time	Nutrient Retention	Color & Appearance	Energy Efficiency	Notes / Limitations
Vacuum Freeze-Drying	-40 to +40 °C	Long	Excellent (VC, flavonoids preserved)	Excellent (minimal color change)	Low to moderate (high energy use)	Best quality, but expensive and time-consuming
Spray Drying	140–200 °C inlet	Seconds to minutes	Moderate to good (depends on matrix)	Good if optimized	High (very fast and scalable)	Suitable for powders, less for whole fruits
Pulsed Vacuum Drying	40–80 °C	Moderate	Good (retains antioxidants well)	Good (low browning index)	Moderate	Combines vacuum benefits with shorter time
Infrared Radiation Drying	50–70 °C	Moderate to long	Moderate (better than hot-air)	Moderate (less browning than HAD)	High (effective heat penetration)	Can cause overheating or uneven drying
Heat Pump Drying	30–60 °C	Long	Good (VC, flavonoids preserved)	Good (lower ΔE and browning index)	Very high (energy-saving tech)	Eco-friendly, but slow and costly equipment

**VC*: Vitamin C, *ΔE*: Color difference value, *HAD*: Hot-Air Drying

Conclusions and Recommendations

This comparative review provides a critical assessment of five advanced drying technologies—vacuum freeze-drying, spray drying, pulsed vacuum drying, infrared radiation drying, and heat pump drying—with respect to their application in drying thermally sensitive and bioactive compound-rich materials such as sea buckthorn. The evaluation considered factors including drying efficiency, energy consumption, equipment investment, and final product quality in terms of bioactive retention, color preservation, and structural integrity. Among the drying methods, vacuum freeze-drying consistently achieved the highest retention of bioactive compounds and preserved product structure, making it the method of choice for high-value pharmaceutical or nutraceutical applications. However, its extremely high energy demands and long drying times limit large-scale commercial use. Spray drying demonstrated outstanding potential for liquid or semi-liquid feed materials, offering cost-efficiency and scalability, though it may compromise heat-sensitive compounds due to high inlet temperatures. Pulsed vacuum drying (PVD) emerged as a promising intermediate technology that balances product quality and energy efficiency by reducing oxidation and structural damage during drying. Infrared radiation drying (IRD) enables rapid heat transfer and improved surface drying but can lead to uneven moisture distribution or localized overheating. Heat pump drying, while relatively novel, presents considerable energy savings and environmental benefits; however, the prolonged drying time and equipment cost still pose challenges for widespread adoption.

In view of these findings, the following recommendations are proposed:

1. **Integrated Hybrid Technologies**: Future development should focus on integrating drying techniques (e.g., FIR-assisted PVD or HAD-VFD) to synergize the advantages of each method, thereby enhancing both product quality and process efficiency.
2. **Smart Monitoring and Control Systems**: The implementation of real-time monitoring tools such as low-field nuclear magnetic resonance (LF-NMR) or near-infrared (NIR) spectroscopy can optimize endpoint detection, reduce drying time, and lower energy consumption.
3. **Retreatment Optimization**: Investigate and apply tailored pretreatment methods—such as pulsed electric fields (PEF), enzymatic treatments, or osmotic dehydration—to improve drying kinetics while maintaining the integrity of heat-sensitive bioactives.
4. **Cost-Performance Analysis for Industrial Scaling**: A comprehensive techno-economic assessment is necessary to guide small and medium enterprises (SMEs) in choosing the most cost-effective and sustainable drying technology based on their production goals.
5. **Product-Specific Drying Strategy**: Since sea buckthorn offers diverse products—ranging from freeze-dried powder to ready-to-eat dried fruits—the drying method should be selected according to the intended use and target market, ensuring that both quality and functionality are preserved.

In conclusion, each drying technology holds unique advantages and limitations. A science based, application-oriented approach combining technological innovation with energy-conscious practices will be crucial for developing a sustainable and high-quality sea buckthorn processing industry.

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