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Review

Research Progress of Sea Buckthorn in the Field of Drying Processing

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Highlights

What are the main findings?

- Research on sea buckthorn drying has remained relatively limited in recent years.
- As a typical berry crop, sea buckthorn possesses unique drying characteristics due to its high oil content and thermolabile bioactive components.

What are the implications of the main findings?

- Vacuum freeze drying can effectively preserve bioactive substances in sea buckthorn.
- Drying studies of other berries can provide analogical references for sea buckthorn drying research.
- Further investigations are still needed to enrich the research database of sea buckthorn drying.

Abstract

Sea buckthorn is highly popular due to its rich nutritional content. However, sea buckthorn berries are characterized by thin skins, abundant juice, a concentrated maturation period, and an extremely short shelf life. Therefore, drying has become an important method for the processing of sea buckthorn fruits. The three main drying methods currently used for sea buckthorn—hot-air drying, infrared drying, and vacuum freeze drying—are introduced in detail in this paper. The advantages and disadvantages of each of these processing methods are analyzed. In addition, the existing problems in the research on sea buckthorn drying processes are summarized, and the material properties of sea buckthorn are analyzed. The research progress on the application of new drying technologies in berry materials is also reviewed. Finally, we consider the development direction of sea buckthorn in the field of drying processing, with the hope of providing new insights and references for researchers.

Keywords: drying; processing; berries; Sea Buckthorn; research progress

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1. Introduction

With the implementation of the United Nations Decade on Ecosystem Restoration initiative, programs returning farmland to forest and afforesting barren hills have been promoted worldwide, exerting profound social and environmental impacts [1,2]. *Hippophae rhamnoides* L., a highly adaptable species belonging to the Elaeagnaceae family, can withstand extreme environmental conditions including high temperature, high humidity, intense solar radiation, sandstorms and severe hypoxia [3]. For this reason, it has been widely applied in soil and water conservation as well as desert greening, serving as one of the primary tree species for the Three-North Shelter Forest Program in China [4]. This plant is also extensively cultivated in the United States, Canada, Russia, Mongolia and Northern Europe (Finland, Poland and Germany) [5]. Statistics show that the global cultivated area of sea buckthorn reached 2.403 million hectares in 2021, among which China accounted for 2.141 million hectares with an output of approximately 650,000 tonnes, while the total global production was less than 800,000 tonnes [6]. Studies have demonstrated that increased consumption of vegetables and fruits in daily diets reduces the risk of chronic non-communicable diseases [7]. Sea buckthorn contains a broad spectrum of essential nutrients, including abundant flavonoids, vitamins, proteases, carbohydrates and multiple trace elements [8]. In recent years, sea buckthorn has gained popularity among consumers owing to its anticancer, anti-ageing and anti-inflammatory properties, as well as potential benefits for gastrointestinal and cardiovascular health [9].

Sea buckthorn contains a broad spectrum of essential nutrients, including abundant flavonoids, vitamins, and polyphenols [10]. The flavonoids in sea buckthorn predominantly exist as quercetin, kaempferol and isorhamnetin aglycones [11], and are associated with antioxidant, anti-inflammatory and lipid-lowering bioactivities [12,13]. Sea buckthorn is also well known for its high ascorbic acid (vitamin C, VC) content [14,15]; the absence of ascorbate oxidase in its tissues contributes to the relative stability of vitamin C during processing [16,17]. In addition, sea buckthorn contains various phenolic acids (e.g., protocatechuic, gallic, caffeic and ferulic acids) [18,19], with a total phenolic content ranging from 986 to 1879 mg/100 g [20]. Importantly, flavonoids, VC and polyphenols are heat-sensitive compounds whose retention during drying is of critical concern[21]. Driven by growing public awareness of health, diverse processing technologies for sea buckthorn have been developed [22], accompanied by the continuous emergence of its by-products.

While previous reviews have provided valuable summaries of sea buckthorn drying methods, the present review advances the field by offering: (1) a critical mechanistic assessment of heat and mass transfer barriers specific to sea buckthorn berry anatomy; (2) an in-depth analysis of drying uniformity in combined infrared–hot-air systems with temperature–humidity control; and (3) a structured evaluation of industrial feasibility across different product forms (whole berries, pomace, and juice powders). These aspects have not been systematically addressed in prior reviews.

The literature for this review was retrieved from the Web of Science, ScienceDirect, PubMed, and China National Knowledge Infrastructure (CNKI) databases. The search terms included “sea buckthorn” OR “Hippophae rhamnoides” AND (“drying” OR “dehydration” OR “hot-air” OR “infrared” OR “freeze drying” OR “vacuum drying”). The publication period was set from 2005 to 2026. Inclusion criteria comprised peer-reviewed journal articles and doctoral/master’s theses reporting experimental drying data for sea buckthorn or closely related berry materials. Exclusion criteria included duplicate publications, conference abstracts without full text, and studies unrelated to drying processes. All literature searches were conducted during the conception, drafting and revision of this review, spanning from December 2024 to October 2026.

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2. Current Status of Sea Buckthorn Processing

To date, a wide range of processing technologies have been developed for sea buckthorn. Postharvest fruits are mostly stored frozen or processed into dried fruits, fruit powder, puree, or fruit wine and juice products. Yao et al. [23] investigated the effects of pretreatments and drying methods on the drying characteristics and quality attributes of sea buckthorn. The same research group further explored the impact of low-temperature oxygen-excluding pulping on the quality of sea buckthorn puree, and proposed an ultrafine cryogenic grinding approach to treat the residual sea buckthorn pomace after pulping; incorporating this treated pomace into sea buckthorn fruit powder was shown to improve the nutritional value and storage stability of the powder [24]. Cai et al. [25] optimized the fermentation process of sea buckthorn juice and obtained a fermented sea buckthorn beverage with a mellow, smooth mouthfeel. Nie et al. [26] used seven thick-skinned muskmelon varieties and sea buckthorn to evaluate physicochemical, nutritional and flavour traits of their compound juice and screen suitable muskmelon cultivars for product development. Ref. [27] took sea buckthorn puree as a raw material to evaluate the flavour characteristics, physicochemical indices and antioxidant activity of sea buckthorn functional beverages, and optimized both the fermentation process and beverage formulation.

Beyond primary products such as fruit wine, sea buckthorn can also be further processed into high-value deep-processed products, including microcapsules, sea buckthorn seed oil and sea buckthorn fruit oil. As a functional oil, sea buckthorn fruit oil is extracted along with juice processing and has a distinctive fatty acid profile: it is rich in oleic acid and linoleic acid, and its palmitoleic acid content is markedly higher than that of common vegetable oils [28]. Sea buckthorn seeds contain approximately 5–20% sea buckthorn seed oil, which is commonly extracted via pressing [29] or supercritical carbon dioxide extraction [30]. To enhance the oxidative stability of sea buckthorn seed oil through encapsulation technology, Liang et al. [31] investigated the preparation process of microencapsulated sea buckthorn seed oil. Li [32] developed a formulation combining sea buckthorn with Haematococcus pluvialis, and systematically studied its extraction process, preparation technology, quality specifications, safety evaluation, antioxidant function and storage stability.

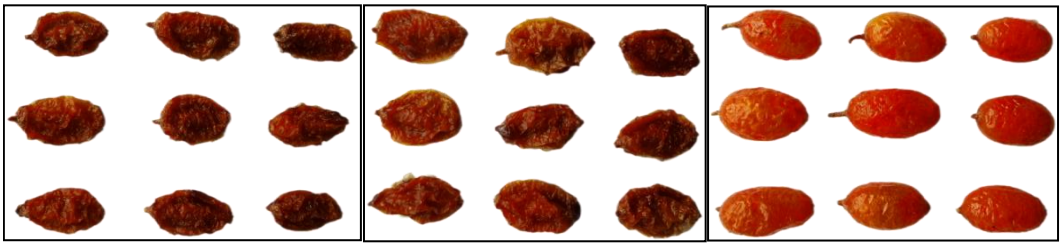
Although both primary and deep-processed sea buckthorn products are abundant, the fruit has thin skin, high juice content, a highly concentrated ripening period and an extremely short shelf life. If fresh fruits are not processed in time, a large proportion will be wasted before they can be converted into marketable products. Drying has therefore become a critical processing step for sea buckthorn fruit. A key challenge currently facing processing enterprises is how to preserve postharvest fruit quality and achieve high-efficiency, high-quality drying. This review aims to summarize the research progress on the drying processing of sea buckthorn fruit, comprehensively analyze the existing limitations of current drying techniques, and discuss future development directions in this field.

3. Current Status of Sea Buckthorn Fruit Drying Processing

Fresh sea buckthorn fruit possesses an extremely high moisture content of up to 80%. It is also rich in vitamins and polyphenolic bioactive compounds yet susceptible to oxidation and microbial spoilage [33,34]. Postharvest fruits cannot be stored for extended periods; at ambient temperature, rapid fermentation and deterioration occur within a short time, resulting in the loss of medicinal properties [35]. Accordingly, extending the shelf life and mitigating postharvest losses remain critical challenges for the sea buckthorn industry. Fruit and vegetable deterioration caused by microbial proliferation and enzymatic reactions is strongly correlated with moisture content [36]. Besides widely adopted strategies such as precooling and fresh-keeping treatments, drying represents one of the most common and practical food preservation techniques known to humans [37]. At present,

the primary drying technologies applied to sea buckthorn include hot-air drying, infrared drying and vacuum freeze drying.

As shown in Figure 1, hot-air-dried sea buckthorn berries (a) exhibit pronounced shrinkage and a dark brown colour, indicating severe Maillard browning and nutrient degradation. Infrared-dried samples (b) show moderate shrinkage with a relatively brighter orange-red appearance, suggesting better retention of colour compounds. Vacuum freeze-dried berries (c) maintain their original shape and bright orange colour with minimal shrinkage, reflecting the superior quality preservation of this method.



(**a**) **Hot-air drying** (**b**) **Infrared drying** (**c**) **Vacuum freeze drying**

Figure 1. Dried sea buckthorn fruit after drying by different methods.

3.1. Hot-Air Drying

Hot-air drying is the conventional drying technique for sea buckthorn fruit. This process achieves heat exchange via air convection and thermal conduction by heating air [38]; meanwhile, increased airflow within the chamber removes moisture from the material to accomplish drying [39]. The system mainly consists of fans, electric heaters, temperature sensors and a display unit, featuring a simple structure, convenient operation and low cost.

As a berry-type material, sea buckthorn fruit has a smooth and dense epidermis, which hinders moisture diffusion during drying and leads to a prolonged drying period [40]. Heat transfer in hot-air drying proceeds from the material surface to the interior through thermal conduction. Consequently, the drying duration is long, nutrients undergo severe oxidation, and product quality deteriorates substantially. Although hot-air drying achieves the highest drying rate among vacuum freeze drying and solar drying [41], the resulting product quality is poor. In practice, natural sun drying and hot-air drying are the most commonly adopted methods for commercial dried sea buckthorn production. Lin et al. [42] compared the effects of multiple drying methods on the drying characteristics and quality indices of sea buckthorn. Their results ranked the drying rates of five drying approaches in the following order: hot-air drying, heat pump drying, natural sun drying, vacuum freeze drying, and natural shade drying. Hot-air drying and heat pump drying require shorter processing times and deliver high efficiency, making them suitable for large-scale industrial drying. Nevertheless, serious nutrient loss and pronounced quality degradation occur after heat pump and hot-air drying treatments.

3.2. Infrared Drying

Infrared drying is a radiative heating method in which electromagnetic waves in the infrared spectrum (typically 2–20 μm) are emitted by a radiant source and absorbed by the material surface. The absorbed radiation energy excites molecular vibrations (particularly O–H, C–H, and C=O bonds), converting electromagnetic energy directly into thermal energy within the material. This volumetric heating mode raises the internal temperature rapidly, creating a temperature gradient that drives moisture from the interior toward the surface [43,44]. This heating process requires no heat transfer medium and enables efficient heat transfer under vacuum, atmospheric and high-pressure conditions. When properly designed and controlled, it can improve heating uniformity compared to

conventional hot-air drying [45]. Compared with convective heat transfer, infrared radiative heating eliminates the thermal resistance induced by thermal and flow boundary layers. Under optimized operating conditions (specific infrared wavelengths and power densities), the energy flux density of infrared heating can be substantially higher than that of conventional convective heat exchange. This method exhibits high heating efficiency and potential energy-saving benefits.

Only a limited number of published studies have reported the application of infrared drying to sea buckthorn. Zhang et al. [46] demonstrated that far-infrared rapid drying of sea buckthorn pomace retained a high proanthocyanidin content while minimizing fibre formation. Integrating infrared drying with hot-air drying can combine the advantages of both technologies and effectively improve drying efficiency. Li [47] designed an infrared–hot-air drying chamber for sea buckthorn. This combined drying system improved drying efficiency, yet severe fruit shrinkage was observed after drying, and excessively high drying temperature markedly impaired final product quality.

3.3. Vacuum Freeze Drying

Vacuum freeze drying is an emerging technology recently adopted for sea buckthorn drying [48]. It operates by reducing temperature and pressure and comprises two primary stages: pre-freezing and primary drying [49]. In the pre-freezing stage, the material is cooled below its eutectic point, and liquid water is converted into solid ice. During vacuum freeze drying, solid ice in the material sublimates directly into water vapour to remove moisture. When the material temperature remains below the triple point of water, its colour and appearance barely change. This technique effectively inhibits enzymatic browning, non-enzymatic browning and protein denaturation, thereby preserving nutritional value [50] and maintaining an attractive visual appearance.

Vacuum freeze drying can well retain the original colour of sea buckthorn products and minimize losses of VC and other bioactive components [51]. One study reported that the nutrient retention of fresh sea buckthorn pomace reached the highest level under vacuum drying [52]. Another investigation identified vacuum freeze drying as an ideal processing method for sea buckthorn fruits [53]. This technology preserves the fruit appearance and VC content close to those of fresh samples, while maintaining abundant vitamin E. Furthermore, Araya-Farias et al. [54] concluded that this method yields superior outcomes relative to conventional hot-air drying. Wang et al. [55] found that vacuum drying of fresh sea buckthorn pomace at 60 °C and 80 kPa with a material thickness of 1.0 cm increased total flavonoid and proanthocyanidin concentrations to 4.98 mg/g and 35.67 mg/g, respectively. It should be noted that these values represent concentrations in the dried material and may reflect water removal rather than true retention; readers should interpret these values as concentrations rather than retention rates. Zhang et al. [53] conducted vacuum freeze drying experiments and verified that setting the pre-freezing temperature to −35 °C, material temperature to 50 °C, shelf temperature to 40 °C and sublimation drying time to 30 h effectively avoided shrinkage and slurry leakage. The resulting dried products possessed appearance and sensory properties highly similar to fresh sea buckthorn. Meanwhile, Zhou et al. [52] reported that freeze drying without heating better preserved flavonoid fractions in extracts; however, both low and high temperatures may trigger losses of these compounds. Nevertheless, vacuum freeze drying suffers from expensive equipment and low productivity [56]. Its operational cost is substantially higher than that of conventional drying techniques, which restricts widespread industrial adoption.

4. Challenges in Mechanical Drying of Sea Buckthorn

At present, only a limited number of drying technologies are available for sea buckthorn fruit. Most drying practices still rely on natural drying, hot-air drying and freeze

drying. Natural drying suffers from a long processing cycle, while hot-air drying induces substantial degradation of VC, total phenols, flavonoids and other nutrients. Vacuum freeze drying is constrained by high capital and energy costs and poor scalability. Therefore, it is essential to develop drying equipment tailored for sea buckthorn and explore optimized drying processes.

During sea buckthorn drying, multiple interrelated mechanisms govern the process. Mass-transfer resistance arises primarily from the waxy cuticle and dense epidermis, which create a barrier to outward vapour diffusion. Shrinkage occurs as moisture is removed, compressing internal pores and reducing porosity, further impeding moisture migration. Case hardening—the formation of a dry, rigid surface layer—is particularly problematic at high initial drying rates, as it seals the surface and traps internal moisture. Temperature gradients between the surface and interior create thermal stresses that can cause structural cracking. The high oil content of sea buckthorn (seed oil 5–20%, fruit oil rich in palmitoleic acid [28,29]) adds complexity: oil migration to the surface during drying can form a hydrophobic layer that inhibits moisture evaporation, while uneven dehydration causes oil–moisture mixing and powder caking during subsequent milling.

Sea buckthorn is a small berry characterized by a high moisture content, long drying duration, poor product quality and high energy consumption. During drying, uneven dehydration frequently occurs within a single material tray: some fruits become over-dried while others remain incompletely dehydrated. This heterogeneity causes mixing of moisture and oil during subsequent pulverization, resulting in caking of sea buckthorn powder. Accordingly, this review compiles an extensive literature to address the challenges of long drying time and inferior quality in sea buckthorn processing. With the goals of improving drying efficiency, reducing energy consumption and preserving product quality, this work seeks advanced drying alternatives to conventional hot-air drying for sea buckthorn to cut drying energy demand. Throughout this review, reported nutrient values are presented as concentrations. Readers should note that higher concentrations in dried products do not necessarily indicate better preservation, as water removal concentrates remaining solutes, and drying-induced structural changes can alter extractability.

5. Future Perspectives of Mechanical Drying for Sea Buckthorn

Sea buckthorn fruit is a typical berry material for drying. A berry is defined as a type of fleshy fruit derived from the ovary, with contributions from other floral organs, and is characterized by a thin exocarp, while the mesocarp and endocarp are succulent and fleshy. To prevent exudation and permeation of internal juice, berry fruits are usually covered with a dense waxy cuticle on the epidermis. This structure hinders the outward diffusion of internal moisture during drying, thereby prolonging drying duration and causing severe quality deterioration. As summarized in Table 1, numerous domestic and international studies have investigated the drying characteristics and product quality of berry materials.

Table 1. Effects of different drying methods on drying characteristics and quality of berry materials.

Material	Drying Method	Main Findings	Reference
Goji berry	Hot-air drying, microwave drying, vacuum freeze drying	Goji berries treated by hot-air drying and microwave drying retained high polysaccharide contents, and abundant Maillard reaction intermediates were formed during drying. Vacuum freeze-dried samples exhibited superior sensory quality but lower nutrient contents compared with the other two drying approaches.	[57]
Blueberry	Vacuum freeze drying	Significant differences in total phenolic and total flavonoid contents were observed between fresh and dried blueberries. Vacuum freeze drying yielded high total phenolic contents. Higher drying temperatures resulted in better retention of total phenols and flavonoids than low-temperature drying.	[58]

Mulberry	Microwave drying	The Midilli and Kucuc model provided the best fit for drying kinetic curves. Microwave drying at 360 W achieved optimal performance. The effective moisture diffusivity (D_{eff}) ranged from 4.97×10^{-8} to 2.60×10^{-7} m²/s, and the drying activation energy was 13.15 kW/kg.	[59]
Grape	Microwave vacuum drying	D_{eff} varied from 1.02×10^{-9} to 4.64×10^{-9} m²/s; both D_{eff} and drying rate increased with elevated microwave power and reduced sample load. The Page model accurately described and predicted moisture changes in seedless white grapes during microwave vacuum drying.	[60]
Raspberry	Hot-air drying, freeze drying, ultrasound-assisted vacuum drying	Ultrasound-assisted vacuum drying required shorter processing time and preserved brighter colour than freeze drying and hot-air drying. Freeze-dried raspberries possessed the highest content of bioactive compounds. Ultrasound-assisted vacuum drying and freeze drying induced lower shrinkage and less cellular damage.	[61]
Strawberry	Solar drying, shade drying, microwave drying	Shade drying took the longest time, followed by tunnel-type solar drying, while microwave drying had the shortest duration; higher microwave power shortened drying time. Higher air temperature accelerated the drying rate. The Weibull model exhibited the best fitting performance for drying kinetic curves.	[62]
Cranberry	Hot-air convective drying, microwave vacuum drying	Microwave vacuum-assisted hot-air drying reduced drying time by 54% relative to hot-air convective drying. Applying microwave energy at the final drying stage increased the drying rate by 17-fold compared with the initial convective stage. Microwave vacuum-dried berries maintained high contents of polyphenols, flavonoids and anthocyanins as well as strong antioxidant activity. Microwave vacuum-assisted hot-air drying yielded better colour of cranberries than hot-air convective drying.	[63]
Cherry	Solar convective drying	Under solar convective drying, the D_{eff} of cherry was 2.85×10^{-9}–6.51×10^{-9} m²/s, and the drying activation energy was 2388.67 kJ/kg. The Midili–Kucuk model was the most suitable mathematical model for cherry drying.	[64]
Cherry tomato	Solar drying, hot-air drying	The Henderson model well described the hot-air drying process at 60 °C. Hot-air drying at 70 °C produced dried cherry tomatoes with higher lycopene extraction yield, whereas samples dried at 60 °C retained higher VC and total phenolic contents.	[65]
Fig	Evacuated-tube indirect solar drying	The mixed-mode solar drying system with evacuated-tube collector achieved superior thermal performance for fig drying compared with the indirect mode, with comprehensive enviro-economic indicators analyzed.	[66]

Numerous studies have reported the effects of diverse drying methods on the drying characteristics and quality of typical berry materials including goji berry, blueberry, grape and cherry tomato. Xie et al. [67] investigated the impacts of different drying strategies on the drying quality of goji berries. Their results demonstrated that vacuum pulsed drying effectively inhibited sugar exudation and browning, yielding dried berries with brighter colours and higher rehydration ratios. At identical drying temperatures, vacuum pulsed drying shortened drying time by 73.2% compared with hot-air drying. Zhao et al. [68] compared the quality attributes of blueberries dried by hot-air drying and infrared drying. It was found that infrared drying resulted in significantly lower bioenzyme activity and reduced degradation of anthocyanins relative to hot-air drying. Xie et al. [69] explored the influences of various drying processes on the drying characteristics of grapes. The Page model satisfactorily simulated grape drying behaviour. For Centennial Seedless grapes, the effective moisture diffusivity D_{eff} under sun drying and shade drying was 6.02×10^{-8} m²/h and 1.89×10^{-8} m²/h, respectively. For Thompson Seedless grapes, the corresponding D_{eff} values were 6.62×10^{-8} m²/h and 8.31×10^{-9} m²/h. Hu et al. [70] evaluated two drying approaches (hot-air drying and vacuum freeze drying) for cherry tomatoes. Vacuum freeze-dried samples exhibited higher retention of VC and better colour performance. Scanning electron microscopy observation of cellular structure revealed that vacuum freeze-dried cherry tomatoes possessed a porous spongy microstructure.

For berry materials, pretreatments prior to drying can effectively accelerate drying rate and preserve product quality. Tekin-Cakmak et al. [61] compared hot-air drying, vacuum drying, ultrasound-assisted vacuum drying and freeze drying for raspberry quality. Drying method exerted significant effects on drying duration, retention of bioactive compounds, physicochemical properties and colour in raspberries. Ultrasound pretreatment shortened drying time and improved the retention of bioactive constituents. Wang et al. [71] applied high-temperature high-humidity air-jet impingement blanching as a pretreatment for Thompson Seedless grapes. They examined pretreatment effects on phytochemicals including chlorophyll, VC and total phenols, as well as antioxidant capacity. The results showed that high-temperature high-humidity air-jet impingement blanching increased total phenolic content and antioxidant capacity both during pretreatment and after drying. Although pretreatment technologies can boost drying rate, they are more suitable for berries with thick cuticles covered by waxy layers. Sea buckthorn has a thin epidermis and abundant juice, which may limit the applicability of such pretreatments.

In summary, the published literature confirms that different drying methods exert distinct influences on the drying characteristics and final quality of berry materials. For sea buckthorn, a typical berry fruit, resolving the barrier effect imposed by its epidermis on drying rate and product quality is of great importance. Geng et al. [72] investigated infrared combined hot-air drying of sea buckthorn with temperature and humidity control to optimize drying uniformity and processing parameters. This integrated strategy may represent a promising direction for future sea buckthorn drying processing. Studies have shown that infrared radiation, as a penetrative heating mode, can disrupt fruit epidermal structure under certain operating conditions [73]. It facilitates outward moisture diffusion from the interior of thin-skinned, juice-rich sea buckthorn fruits, accelerates drying rate and shortens processing time, which is highly favourable for sea buckthorn drying. The effects of humidity control are stage-dependent. In the early drying stage, when the fruit surface is still moist, elevated relative humidity can increase the enthalpy of the drying medium and accelerate initial heating, potentially reducing the risk of rapid surface crust formation (case hardening). However, increasing air humidity reduces the vapour pressure difference between the material surface and the drying air, thereby decreasing the moisture-driving force—this effect becomes detrimental in the later drying stage when internal moisture diffusion is rate-limiting. Therefore, humidity control should be applied selectively: higher humidity at the initial stage to prevent case hardening, followed by reduced humidity to maintain the drying driving force in subsequent stages [72]. Considering the high oil content of sea buckthorn, temperature–humidity-controlled drying may reduce drying duration and mitigate lipid oxidation and powder caking caused by uneven dehydration. This improves drying uniformity, mitigates nutrient degradation and avoids incomplete or over-drying phenomena.

6. Conclusions

Driven by market demand and industrial development, large-scale sea buckthorn cultivation has expanded in Northwest China in recent years. Nevertheless, scientific theories and design methodologies that can provide precise practical guidance for sea buckthorn drying technologies remain insufficient, and industrial operations still largely rely on empirical experience. Sea buckthorn is characterized by high moisture content and poor storability, which makes drying its primary processing method. However, existing research has certain limitations. The fruit epidermis substantially restricts drying rate and product quality. During drying, moisture content varies greatly across different drying stages. Rapid drying in the early stage readily induces surface crust formation, which severely hinders subsequent internal moisture diffusion and triggers quality deterioration.

High standards for product quality are required in agricultural product processing, demanding precise processing conditions. Drying is a complex process involving moisture transfer within a material and heat transfer to the material, governed by heat and mass transfer resistances between the fruit matrix and the drying medium. Therefore, improving the reliability of drying operations in the future relies on the underlying heat and mass transfer mechanisms, and innovative approaches should be developed at the mechanistic level. Future research and practical applications should also consider the effects of material-specific properties on drying behaviour.

It should be noted that limited research is available regarding temperature- and humidity-controlled drying of sea buckthorn among the future prospects outlined in this review. Further in-depth feasibility investigations are still required. Future research on drying technologies for sea buckthorn should pay more attention to combined and novel drying methods. At present, direct quantitative comparisons of drying time, energy consumption, product quality and industrial application potential among different drying approaches remain insufficient in the existing literature. Further systematic comparative studies are required to clarify the trade-off relationship between technical performance and economic benefits, which will facilitate the industrial translation of drying technologies.

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