Progress on research and development of goji berry drying: a review

Chaojing Cui, Dandan Zhao, Jin Huang, and Jianxiong Hao

College of Food Science & Biology, Hebei University of Science & Technology, Shijiazhuang PR China

ABSTRACT
Goji berry, as a kind of typical and special agricultural material, has high water content, high sugar content, thin epidermis with waxy covering, and dense fleshy cell structure, which makes the drying process more complex than the dehydration of other bio-materials. To obtain high drying efficiency and the high quality products, most researchers have paid much attention on the different kinds of pretreatment and drying technology. This study aimed to examine all the corresponding published data in the literature and to compare the drying characteristics and quality of wolfberry dried by conventional and advanced wolfberry drying methods as well as different drying parameters. We conclude that heat pump drying with simultaneous control of temperature and humidity could replace traditional hot air drying in commercial production to increase the drying efficiency and quality of wolfberry. Infrared drying and microwave drying can be combined with other drying methods to improve drying efficiency; freeze drying, pulsed vacuum drying and electro-hydrodynamic drying are conducive to maintain the appearance and nutrients as well as higher rehydration ratio because of more porous microstructure compared with hot air drying. In addition, this study gives some suggestions and new horizons for directed wolfberry drying development both on the research and application in the future.

ARTICLE HISTORY
Received 4 October 2021
Revised 27 January 2022
Accepted 19 February 2022

KEYWORDS
Wolfberry; Drying kinetics; quality; Research progress

Introduction
Goji berry (Lycium barbarum L.), also known as Chinese wolfberry, Lycium fruit, and Desert-thorn, is a member of the nightshade family, Solanaceae. Generally, goji berries are found in dry and semi-saline areas. In Asian countries, mostly in China, goji berry is not only a kind of tonic food but also a well-known traditional medicine for more than 4000 years. The medicinal effects and remarkable health benefits of Goji berries, like nourishing the blood, moistening the lungs and improving vision, have been recognized and appreciated by numerous medical scientists in the history of China.

Several decades ago, goji berry is mainly used for garden decoration in the west, due to the lack of scientific support regarding its purported health benefits. But recently more and more bioactive components in goji berry have been identified and evaluated, making western market interest in goji berry rapidly intensified. Polysaccharides represent the most important group of nutrient in goji berry, and till now, more than 30 polysaccharides have been isolated from different species. Carotenoids present in goji berry are the second highly significant group of bio-active constituents, which are derived from the reddish-orange color of fresh goji berry. Moreover, the presence of other phytochemicals like flavonoids, alkaloids, amides, lignanoids, organic acids have also been confirmed. Currently, goji berries are more consumed as a “superfruit” to decrease blood...
glucose and lipid level, \cite{12,13} stimulate anticancer cells, \cite{14} protect vision \cite{15} or increase mental efficiency. \cite{16} Goji berry would have the noteworthy potential for staying power as a nutritional food likely to draw more attention to scientific validation and various product developments.

Similar to other fruits in berry group, the fresh goji berry has high water content around 80% and tender tissue. The annual production of fresh goji berries are over 200,000 t in China\cite{17} but they deteriorate promptly after harvesting due to chemical alterations and microbial spoilage. \cite{18} A wide range of goji berry products has been produced, including tea, wine, milk, cosmetic products, coffee, and juice, but dried goji berries are the most popular products and are consumed around the world. For longer shelf life and wider selling network reasons, drying becomes one of the important techniques for goji berry processing, which can also meet the requirements of high-efficiency industrial production and space reduction.

The completely mature fresh goji berries are bright-red color and juicy in taste. Considering ready-to-eat and deep-processing goji berry products, which are consumed in a dry state, the importance of quality indices become evident. \cite{19} The quality of dried goji berries is commonly assessed in terms of the appearance, flavor, texture, cleanliness and nutritional values. The quality of dried goji berries are commonly assessed in terms of the appearance, flavor, texture, cleanliness and nutritional values, which will determine the price and consumption quantity in the market. Apart from species differences, harvest condition and some individual preference, the quality of dried goji berries are highly affected by drying process and storage environment before consumption. \cite{20} Texture always depends on the drying method and final moisture content in the product; color, flavor and nutritional values could be influenced by the state of the fresh goji berries and drying parameters \cite{21}, and cleanliness is often impacted by processing and storage environment. However, as transportations become super-speed and innovative storage technologies appeared recently, the role and function of the drying process have to be highly regarded.

Drying of goji berries varies in different areas of the world, depending on many factors. Intending to remove water from foodstuff, conventional drying methods are more focusing on using high temperature and long drying time. \cite{22} But typically, fruits like berries are rather heated sensitive, so the higher temperature may result in irreversible changes of the structure, color, flavor of final products. \cite{23,24} Recently, the increasing consumer’s awareness and market demand accompanied by progress in drying facilities provide researchers with opportunities to develop a range of new drying methods and goji berry products. \cite{25} Some advanced drying methods, like vacuum freeze drying and heat pump drying, were reported for drying goji berry by lower temperature, shorter drying time, less energy-intensive and better product stability. \cite{26–28} They showed us the big potential for future use by the food industry, but there are still some challenges, such as complex drying system, large equipment investment and high technical operation required, which impede the popularization and application of these new drying methods. \cite{29} Besides, fresh goji berry are short in fruiting period and storage period, therefore, the production yield should also be considered in the industrial application of drying technology. Thus, the balance between economic performance and high quality products become our concern in goji berry drying. Until now, obviously, many types of research focusing on the health benefits of goji berry, but the quality of dried goji berry products are significantly influenced by drying methods. However, limited information is available on goji berry drying method, equipment, and dried goji berry quality changes. Therefore, this study aims to 1) detailed introduce conventional and advanced goji berry drying methods. In particular, to focus on the drying parameter, drying equipment requirements with respect to product quality; 2) identify the advantages and disadvantages of different drying methods, for an optimization of goji berry drying operation; and 3) give some suggestions and new horizons for directed goji berry drying development in the future.

**Skin structure and pretreatment**

**Skin structure:** Generally, the skin structure of goji berry play an important role in controlling the drying process. \cite{30} Nevertheless, little information could be found in the literature regarding the anatomic study of goji berry skin. So far, researchers only found that goji berry has a specific epidermal structure covered
by a thick layer of longitudinally folded cuticle and a thin layer of wax.\cite{31} The waxy constituent of the skin, acts as a protective barrier against fungal pathogens and water loss naturally for goji berry,\cite{20} inhibiting the moisture movement across the membrane during drying process afterward.\cite{32} The microscopic structure study indicated that the wax layer of goji berry was thick, smooth and neat bundles, closely arranged and attached with a lot of wax debris. Once the wax layer is completely removed, the cuticle can be exposed.\cite{33} Although the existence of wax layer in the goji berry skin is a barrier to drying, it is still important to concern that their removal by pretreatment process requires close attention due to their strong effect on the storage life and safety of the dried goji berry products.\cite{20}

**Pretreatment:** The presence of the wax outer peel layer in goji berry skin may lead to a high-temperature and time-consuming drying process. High drying temperature and long exposure time can cause a quality attributes loss of the dried goji berry products.\cite{34} Thus, it is essential to find safety pretreatment methods to remove the wax layer, enhancing the rate of water movement during the drying process. Refer to grape\cite{35} and prune\cite{36} pretreatment methods, Adiletta et al.\cite{32} used a physical wax abrasive pretreatment to carefully remove the wax layer from fresh goji berry. The results showed that the dried goji berries were obtained in less time when they were pretreated, preserving better color, increasing the antioxidant activity with respect to the untreated case. Compared with physical methods, there is growing interest in the usage of chemical pretreatment, because it only takes a few minutes for chemical solutions (mainly containing alkaline emulsion) to dissolve the wax layer of goji berries. Li et al. compared sodium carbonate solution with sodium sulfite solution as wax removers to smear the surface of the pure fruit of *Lyceum barbarum* L. The results indicated that the goji berry with sodium carbonate solution had a higher drying rate in an early stage. Similar to grape, goji berries can also be dipped in sodium hydroxide solution\cite{37} or potassium carbonate solution,\cite{38} which can induce breakage of the skin favoring the mass transfer.\cite{27} Therefore, it appears that there are various choices may lead to different microstructural changes of goji berry skin. Knowledge of these differences is necessary to be identified to improve dried goji berry quality. Above all, both physical and chemical approaches showed their potential to partly remove a wax layer from goji berry skin for improving drying speed. But the physical method is too energy intensive while chemical methods may also cause food safety and environmental waste problems. Thus, further improvements are still required.

**Drying methods**

Conventional drying methods: There are two main conventional drying methods that are widely used in goji berry production in the history, sun drying (solar drying) and hot air drying (HAD).

**Sun drying (solar drying):** Sun drying is one of the oldest preservative techniques in the world. It has been used since time immemorial to dry many agricultural products,\cite{39} which also including goji berries. The simplest operation of sun drying is spread the fresh goji berries in thin layers in the sun after the goji berries are harvested. Then, the solar radiation heats up the goji berries as well as the surrounding air and therefore increases the rate of water evaporating from the fruits. Generally, goji berries are preserved for about 5 days, until the outer skin becomes hard and plicated but the pulp remains soft.\cite{40} However, the simplest goji berry drying process has many shortcomings such as weather uncertainties, insect infestation, and dust contamination, which make it inapplicable in many areas.\cite{39} Then, multiple types of solar energy drying device be invented.

The most common use solar drying device for goji berry in China is greenhouse type solar dryer. The solar dryer actually has a solar greenhouse humidity discharging capacity, whose heat collecting part and the drying chamber are combined into a whole. The top of the dryer is a large area of tilt glass cover, while the wall on the ground is arranged a certain number of vents.\cite{41} Ran et al.\cite{42} designed and tested a greenhouse solar dryer based on characteristics and requirements of Chinese wolfberry. The results showed the solar dryer can shorten the drying cycle from 120 hours to 24 hours compared
with the traditional sun drying process. In addition, the development of sun drying devices for goji berry production can also overcome disadvantage factors caused by weather changes and the pollution from natural sun-cure.  

In general, sun drying has its own superiority which all other methods are unable to compare. Since solar energy is abundant, inexhaustible, renewable and non-pollutant, sun drying is cheap and environmentally friendly. Meanwhile, few special requirements of drying facility make the low capital investment and simple operation of sun drying, which are distinct advantages in goji berry drying history. However, sun drying is not always suited to dried goji berry production. There are also some problems in sun drying such as the slowness of the process, lack of ability to control the drying operation properly, large area requirement, pollutions and so on. So till now, sun drying is still practiced in many places throughout the world where solar radiation is convenient, but not fitted to modern industry large-scale production. Maybe the further research about solar drying devices can partly make up for the deficiencies of goji berry sun drying application.

**Hot air drying (HAD):** HAD, in particular, is an ancient process used to preserve goji berries. The hot-blast stove is used to heat air and send the hot air to fresh goji berries, making moisture evaporates. This is a kind surface heating process while temperature gradients are present within the material. The surface of goji berries is exposed to drying temperature directly for much longer time than the interior of the fruit, which may be used to create special properties of the dried goji berry products. Jia et al. reported that drying air temperature is a major factor which influences the drying speed, and the wind speed is a factor of secondary importance. Wu et al. investigated the HAD characteristics of goji berry and the results showed that the drying time of goji berry decreased largely from above 48 h to 15 h with the increase of air temperature from 40°C to 60°C. Compared with sun drying process of goji berry, HAD may be regarded as a quick drying process because it can highly shorten the drying time, then expand production for industry. But there are also many disadvantages of this drying method. Rapid reduction of surface moisture may result in consequent shrinkage while prolonged exposure to elevated drying temperatures could lead to substantial degradation in goji berry quality attributes, including sensory characteristics (color, flavor, texture) and nutritional values. Overall, HAD is a great step forward compared to sun drying, but the process needs more explorations and innovations for further applications in dried goji berry industry.

**Advanced drying methods:** New and advanced drying techniques that decrease the drying time and enhance product quality have achieved considerable attention in the recent past. Currently, many innovative drying methods, such as microwave drying, heat pump drying, freeze drying and infrared drying have been applied to goji berry and showed the immense potential for the prospective market.

**Microwave Drying:** Microwave drying method has gained a renewed interest in both academia and industry because of the unique volumetric heat generation and the increased mass transport. These characteristics are proved to be advantageous for many materials over traditional drying methods, such as kiwifruits, banana, carrots and cranberries. Microwave drying processes are commonly carried out with a digital microwave oven with diverse technical features. The size and shape of the food materials may affect the temperature distribution during drying process; therefore, the microwave oven is able to work at various microwave outputs and has a digital control facility into adjusting the processing time according to the wet products.

Ma et al. studied the drying of Chinese goji berry using a single mode microwave. The experiments were carried out by controlling the microwave heating power and material thickness and monitoring the temperature. The results found that microwave drying can significantly shorten the goji berry’s drying cycle in the falling rate drying stage. The higher dried goji berry quality can be maintained when the heating power is 1 kW and the material thickness is 2 cm.

Microwave drying has many abilities to gain popularity in food processing, such as high heating rates, a significant reduction in drying time, more uniform heating, safe handling, ease of operation. On the contrary, there are also some reasons for its limited use like high initial costs for industrial scale dryers and special care to shield operators from the microwave radiation. At present, microwave assisted with other drying methods such as air drying, vacuum drying and freeze drying gave better drying characteristics for
some materials compared to microwave drying alone, so more research could be also carried out for a better understanding of microwave assisted drying system and goji berry drying characteristics, and hopefully a pilot scale level of microwave dried goji berry production can be developed.

**Heat pump drying:** The heat pump has evolved to become a mature technology over the past three decades. Due to the abilities to recover energy from the exhaust and control the drying gas temperature and humidity independently, more and more researchers have acknowledged the importance of heat pump drying technology to dry a wide range of products and improve their quality. So far, there are some heat pump applications in food industrial manufacturing activities like beer brewing, wet corn milling, and juice manufacturing have been achieved. And a newly developed goji berry product quality must conform to a wide consumer’s preference.

Heat pump dryer is a co-existence of two engineering systems: the heat pump and the dryer. Conventionally, a mass of energy loss is not avoidable for hot air dryer because the process air at relatively high temperature has to be vented off from the dryer. But if the dryer is equipped with a heat pump, the energy at the dryer exhaust can be recycled easily. As for heat pump itself, there are also four main components exist the evaporator, the compressor, the condenser and the expansion valve. All the facilities working together as a cycle to dry the materials and recovery the energy, making the drying system more particular and efficient. Commercial heat pumps based on the vapor compression cycle or the absorption cycle are operational in numerous applications for various industries. And equally, for certain materials, there should be a corresponding system design to increase energy efficiency and improve qualities.

Based on the heat pump drying characteristics of Chinese goji berry, Zhao et al. designed and established a large heat pump drying room which could supply abundant heat and precisely control temperature and humidity. The design is highly suited to meet the needs of wolfberry drying process. In this study, they found that it was reasonable to set 1.0 as a turning point at the drying stage, if the moisture content of goji berry on a dry basis was higher than 1.0, the set temperature should be maintained around 52°C, if the moisture content was arrived at or below 1.0, the temperature of drying room could continue to rise. Compared with the wolfberry dried in the coal chamber, samples dried by heat pump drying room had higher overall quality and the drying time was reduced by 20% and drying costs were reduced by 19%, hence the conclusion was heat pump drying process was reasonable and heat pump drying room could be applied to production practice.

To sum up, considering about the climate change and air pollution, heat pump drying can be a good choice for dried goji berry production as the heat recovery results in lower energy consumed for each unit of water removed. Moreover, it was proved that well-controlled drying conditions of heat pump drying method benefit heat-sensitive materials like goji berry and can significantly produce better product quality. However, it is not applied as widely as it should or could be because of the following reasons: frequent maintenance of the compressors, refrigerant filters, heat exchangers to keep the dryer in optimum operating condition; refrigerant leak risks and capital investments. Thus, for prospective utilization in goji berry industry, initial and operating costs of heat pump drying technology require further reduction, namely cost-competitive heat pump dryers should be designed and constructed in the future. It is strongly believed that the potential of heat pump drying in goji berry production has been significantly under-exploited.

**Freeze drying:** Among the drying methods that are used in food processing industries, freeze drying is considered one of the most advanced methods for drying high-value products sensitive to heat. Two stages are carried out normally during freeze-drying: the products are flash frozen at first and then the ice is removed from the solid to the vapor phase directly by sublimation. So far, freeze drying method has been applied to dehydrate various agricultural products like carrot, rice, potato, mushroom and strawberry, since it avoids using high temperature, so the undesirable shrinkage of materials can be prevented, and the quality of products can be improved with unchanged nutrition quality, better taste, flavor and color retention.
To freeze-dry goji berry, firstly the fresh goji berry is rapidly frozen at a low temperature to −45°C, then under a certain vacuum condition, the frozen water sublimates directly into the overflow to achieve the purpose of drying, while the goji berry itself is left in the frozen ice shelf. Therefore, the dried volume of goji berry wouldn’t be changed. Anaïs Chassaing et al.\cite{69} compared different drying technologies on the preservation of polyphenolic antioxidants from goji berries and found freeze drying enabled the best preservation of bioactive compounds. Due to the special characteristics of the freeze-drying method, dried goji berry shows the great difference on its properties comparing with oven-dried and air-dried. Freeze dried goji berry becomes loose, porous with good rehydration performance and crisp mouth feel, retaining the color, aroma, taste, shape, and nutrition of the original fresh fruits. Instead of soft pulp, the internal pulp and fruit seed of freeze-dried goji berries are dry and dispersed gives fruity scent. After soaking the freeze-dried goji berries into warm water, it can be observed that dried goji berry absorbs water easily and quickly restore to the original state, then the flesh floating on the surface of the water.\cite{70}

Overall, the advantage of freeze-drying goji berry is that the original shape, taste, flavor, and nutrition of the berries are preserved quite well compared with other drying methods and in addition,\cite{71} the final consumers can discover a very different dried goji berry product with crispy structure, which may open new business opportunities for goji processors. However, the frail and crumbling texture can also become a disadvantage, because dried goji berries keep their original shape and size, meaning that they might require extra transportation and storage space and also special package. Moreover, considering the expense, the equipment needs for goji berry freeze-drying process requires very low temperature and certain vacuum condition, which can be really costly. In a word, more viable freeze-dried goji berry products can be developed and cheaper equipment should be exploited. The predominance of exploiting the potential of freeze drying will be determined in the near future.

**Pulsed vacuum drying (PVD):** During PVD drying, materials are placed in the drying chamber where the pressure alternate between high and low. There are two heating methods: heating plate and infrared heating. The length of the time for single pressure cycle depends on the properties of the dried material (chemical composition and structure) and drying technology (drying humidity, heat transfer, and vacuum degree).\cite{72} As the materials are in a low-pressure vacuum environment for the most of the time, water evaporates at a lower boiling point under vacuum conditions and the oxidation browning can be effectively inhibited, which improves the drying efficiency and reduces the loss of nutrients. Furthermore, the reciprocating cycle of pressure is conducive to the disturbance of water vapor partial pressure, breaking balance of partial vapor pressure between the material and the medium, which helps to expand the microchannel of the material, thus promoting the moisture migration rate and also improving the rehydration ratio and the brittleness. In recent years, the PVD drying has sparked intense interests of the researchers and has been applied in some fruits and vegetables like rhizoma dioscoreae slices,\cite{73} bitter orange slices\cite{74} and blueberry.\cite{75} Xie et al. had studied the effects of drying temperature and pulsed vacuum ratio on PVD characteristics and quality attributes of goji berry, showing that PVD is a promising technology for goji berry because PVD can reduce drying time significantly, retain the total polysaccharide content, enhance the color appearance and improve the rehydration ratio.\cite{72} The previous study showed the potential applications in goji berry drying for the higher drying efficiency and better quality compared with HAD or continuous vacuum drying, but the heating method, parameter at different stages, and the changes of the heat sensitive components still need to be further studied.

**Infrared drying:** Gratifying the industrial requirements and consumer demand create the development and improve valid drying methods for goji berry, in order to make the processing more sustainable and maintain good product quality. Talking about drying, convection, conduction, and radiation are the major methods of transferring heat energy.\cite{76} As one of them, infrared radiation energy can be transferred from the heating element to the surface of product, or even penetrates into the food materials, without heating the surrounding air. Thus, infrared drying method gained popularity due to its high heat transfer coefficients, and fast response time drying rate compared to other drying methods.\cite{77} In last two decades, infrared drying has been applied to different food
materials including fruits, [78] legumes, [79] vegetables [80] and grains. [81] Since the experiments related to other berries like blueberry, [82] strawberry [85] and grape [84] by using infrared radiation heating were carried out, there is also a need for more studies concerning goji berry.

Different infrared dryer should be designed specifically for different materials wherein radiant flux density and air velocity could be varied within the necessary range. [77] Anaïs Chassaing et al. [69] studied preservation of polyphenolic antioxidants from Goji berries affected by different drying techniques and found the infrared drying, accompanied with ultrasonic pretreatment for 10 min can be regarded as the best alternative compared with air drying, oven drying and freeze drying, as it shortened the drying time and gained a similar quality dried goji berry products. Xie et al. [85] used a pulsed vacuum dryer with far-infrared radiation heating (FIR-PVD) to dry goji berry, and the results showed under appropriate conditions, FIR-PVD could significantly lower the drying time compared to HAD and natural open sun drying. Moreover, from current research we know, infrared drying can be a promising drying method for goji berry drying without chemical pretreatment, which can make the dry processing more sustainable and environmental friendly. [86]

The findings in current study indicate that infrared drying method has great potential for drying goji berry due to its special heat energy transformation, which can not only save energy and omit chemical usage, but also shorten drying time and improve products quality. But seriously, infrared drying system is very complicated to control and optimize, and also expensive to commercialize. Furthermore, infrared radiation leakage can also be an important consideration for people who want to try this advanced technology because uncontrolled, frequent exposure to infrared can cause some healthy problems such as thermal burns and effects of aging. [87] Thus, the risks and chances coexist in infrared drying technology for goji berry, and further improvements are worth exploring.

**Electro-hydrodynamic Drying (EHD):** EHD is a new, non-thermal drying method that depends on the electric field to transfer mass to achieve dehydration for the biomaterials. In the last decades, EHD has been applied in different food like tomatoes, [88] carrots, [89] sea cucumber [90] and blueberries, [91] showing EHD could reduce drying time and energy consumption, improve quality in terms of shrinkage, rehydration rate, protein and acid mucopolysaccharide content, texture, color, appearance and flavor, and also show ability of inactivation of enzymes. Ni et al. had studied the EHD characteristics of goji berry in a multiple needle-to-plate electrode system, showing that EHD drying is the interaction of ionic wind and a nonuniform electric field, as ionic wind and needle spacing can significantly affect the drying kinetics and quality of products, respectively. [92] Different from thermal drying technology, EHD has obvious advantages in products with high nutritional value, the optimization of drying technology and to achieve industrialization will be the research trends in future.

**Drying kinetics**

Previous study shows that the drying dynamic curve, drying time and effective diffusion coefficient ($D_{eff}$) of wolfberry are affected by the pretreatment method, drying method and drying parameters. The drying time and drying rate of goji berry fruits were significantly affected by drying method, temperature and pretreatment. [62,93–97] With the increment of drying temperature, the drying time decreases and the drying rate increases, Na$_2$CO$_3$ solution pretreatment could reduce the drying time by 22%–28% because of the damage of the waxy layer by lye. It also can be found that there is no constant drying period for goji berry, the whole drying process is mainly a falling rate stage, consisting a low-speed decelerated stage and a high-speed decelerated stage. For example, Zhao et al. [94] studied the drying characteristics of wolfberry dried at 40°C ~ 60°C, showing a falling rate stage consisted of a high-speed drying phase (moisture content, > 3.5 g water/g dry mass), an intermediate-speed drying phase (1.0 g water /g dry mass ≤ moisture content ≤ 3.5 g water /g dry mass), and a low-speed drying phase (moisture content, < 1.0 g water /g dry mass). This is because the rate is determined by internal water diffusion and surface water evaporation. The properties of material including structures, size, and density have a big effect on the mass-transfer phenomena in drying. For wolfberry, which has a thick pulp and dense skin, the rate of internal water diffusion was slower than the surface water.
evaporation rate, leading to a non-constant rate drying period. When the moisture content declines to 1.0 g water/g dry mass, at which point of the free water is almost fully removed and the bond water starts to evaporate, the drying rate shows a rapidly dropping trend. However, most of the articles were measured in a constant temperature and a low humidity condition, Zhao et al.\textsuperscript{[62]} reported that the drying rate of wolfberry dried by a method of gradual rise in temperature and reduction in humidity showed a relatively constant stage (1.0 g water/g dry mass ≤ moisture content ≤ 3.2 g water/g dry mass), which means that proper simultaneously control in temperature and humidity will narrow the gap between the water migration inside and the evaporation in the surface of the material.

The $D_{\text{eff}}$ and energy activation energy ($E_a$) are calculated by Fick’s diffusion equation and Arrhenius equation respectively in the former studies, providing that there is no shrinkage and the effective diffusivity is constant. Hu et al. and Zhao et al. obtained the similar range of $D_{\text{eff}}$, which were $4.13 \times 10^{-11} \sim 16.1 \times 10^{-11} \text{ m}^2/\text{s}$ and $7.6 \times 10^{-11} \sim 19.8 \times 10^{-11} \text{ m}^2/\text{s}$ respectively.\textsuperscript{[94,95]} While, Hesym et al. reported higher values of $D_{\text{eff}}$ between $1.04 \times 10^{-8} \text{ m}^2/\text{s}$ to $2.98 \times 10^{-8} \text{ m}^2/\text{s}$. This may be attributed to that the wolfberry used by Hesym et al.\textsuperscript{[93]} was stored at $-18^\circ \text{C}$ before drying, which may destroy the structure of the material in the process of thawing, leading to a higher transferring and drying rate in the drying process than that using fresh berries stored at $4^\circ \text{C}$.

$E_a$ is another important parameter to evaluate the energy consumption of material drying, which indicates the amount of energy required to remove 1 mol of water from the material. Results show that the type and structure of the material will affect the drying activation energy, and the different pretreatment and drying methods of the same material will also have an impact on the drying activation energy. For example, the activation energy of \textit{Lycium barbarum} treated with an untreated in HAD is 49.65 kJ/mol and 50.7 1 kJ/mol;\textsuperscript{[94]} respectively; the activation energy of microwave-dried wolfberry is 54.78 kJ/mol.\textsuperscript{[97]} Although there have been a lot of researches on the drying experiment of wolfberry, however, the mechanism of water migration in the drying process of wolfberry has not been fully studied.

\textbf{Quality of dried goji berry}

As a semi-processed product, the quality of dried wolfberry is evaluated based on appearance, texture, and nutritional value. In addition to the variety and pre-harvest conditions, the quality of dried wolfberry largely depends on the operation, pretreatment, drying, processing, and storage conditions. After different varieties of wolfberry are dried under the same operating conditions, their quality is also different due to the different texture and composition.

Color is one of the important indicators to measure the quality of wolfberry. Table 1 and 2 summarizes the quality changes of wolfberry with different drying methods discussed in this section. It can be found that the dried wolfberry showed lower values of $L^*$, $a^*$, and $b^*$ compared with fresh ones. Zhao et al.\textsuperscript{[94]} reported the variation trend of color during the drying process, showing that the values of $L^*$, $a^*$, and $b^*$ of wolfberry dried directly by hot-air drying decreased rapidly with the decrease of moisture and then kept stable when the moisture content reached to 1.0 g water/g dry mass. However, the values of $L^*$, $a^*$, and $b^*$ of wolfberry dried by hot-air drying with Na$_2$CO$_3$ solution pretreatment kept steady with the decrease of moisture content and then dramatically decreased after the moisture content reached to 1.0 g water/g dry mass; With the decrease of water content, the total color difference value $\Delta E$ of wolfberry rapidly increased, and the $\Delta E$ value of the sample treated with lye at the same drying temperature is lower than that of the untreated sample. It was also found that low-temperature drying and lye treatment can effectively protect the color. Song et al.\textsuperscript{[98]} analyzed the quality of heat pump and hot air dried wolfberry and found that the color of wolfberry dried by heat pump was better than that of HAD, as the drying temperature increased, the total color difference of wolfberry became larger and the color quality became worse. As with high temperature, the pigment or other color components in the wolfberry are tend to decompose, and the chemical reaction rate is too fast; it may also be that the rapid drying of the wolfberries at high ambient moisture levels causes some irreversible chemical reaction in the ingredients of the wolfberries, the macroscopic manifestation of these chemical reactions is that the color of the wolfberry becomes dull instead of bright red. Li et al.\textsuperscript{[99]} compared the quality of freeze-dried and hot-air drying of wolfberry and
found that the color of freeze-dried wolfberry is bright red, which is close to the color of fresh fruit. However, when using far-infrared to dry wolfberry without pretreatment, the $L^*$ value of wolfberry is generally low, and different pretreatment methods will significantly increase the $L^*$ value of wolfberry. Wang et al. compared the effects of natural drying, coal-fired drying rooms, and solar drying equipment on the drying efficiency and dried fruit of wolfberry and found that the $L^*$ and $a^*$ value of wolfberry dried by solar drying equipment were higher than those of the other two drying methods, it is closer to the value of fresh wolfberry, followed by the wolfberry dried in the coal-fired drying room, the color of the sun drying wolfberry is the worst because the Maillard reaction and dust pollution of the wolfberry during the drying process will affect the brightness and redness of the dried wolfberry product.\[^{100}\]

Color change is the most common change phenomenon in the process of food drying. It is related to the drying method, drying temperature and moisture content. Studying the color change trend during the drying process can provide a reference for improving the color quality of the wolfberry drying process in the future.

*Lyccium barbarum* contains a variety of nutrients, mainly including pigments, flavonoids and polysaccharide compounds, as well as betaine, vitamin C, a variety of amino acids and a variety of trace elements. Zhao et al.\[^{101}\] reported that the content of total phenols, total ketones and DPPH scavenging ability of dried wolfberry obtained by hot-air drying were higher than that of fresh wolfberry, and lysoe soaking treatment could appropriately increase the content of total phenols and total ketones, and improve the oxidation resistance of dry products. The content of flavonoids and the retention rate of polysaccharides and carotenoids of dried wolfberry obtained by heat pump drying were greater than that of HAD, and for flavonoids and polysaccharides, the effect of drying temperature is greater than the drying time, but for carotenoids, the drying time of influence is greater than the drying temperature.\[^{62}\] Compared with natural drying, far-infrared drying can significantly improve the polysaccharide preservation rate of wolfberry, because far-infrared drying is heating both inside and outside, the drying time is short, which greatly reduces the loss of wolfberry polysaccharides during the drying process; and different pretreatment conditions can significantly reduce the loss of *Lyccium barbarum* polysaccharides and betaine during drying, ultrasonic infiltration pretreatment helps to increase the content of polysaccharides.\[^{96}\] Besides, Xie et al reported that the dried wolfberry dried by PVD had higher polysaccharides than that of products dried by HAD, and also had much higher rehydration ratios due to that PVD samples had a more porous surface microstructure.\[^{72}\]

**Conclusion**

*Lyccium barbarum* is a kind of typical and special material, with short harvest period, and the fresh fruit is not easy to store. It contains high sugar with thin epidermis covered with waxy and more compact fleshy cell structure, so the drying time of wolfberry dried by traditional HAD is long, and the quality is not easy to control. However, as hot-air drying is low in cost and easy to operate, it should be studied in depth most for commercial application. In the future, studies should focus on the following aspects: (i) Explore the co-control hot-air drying technology in temperature and humidity, (ii) Study the dynamic change moisture migration characteristics, microstructure and components related to the moisture immigration of wolfberry during hot-air drying, as well as to build their relationship, aiming to clarify mechanism of moisture migration, (iii) Study the dynamic change rule of nutrients in drying process, and study the regulation rule of quality in combination with water migration mechanism. We also conclude that infrared drying and microwave drying can be combined with other drying methods to improve drying efficiency; freeze drying, pulsed vacuum drying and electro-hydrodynamic drying are conducive to maintain the appearance and nutrients as well as higher rehydration ratio because of more porous microstructure compared with hot air drying.
### Table 1. HAD, hot air drying; HPD, heat pump drying; FIRD, far Infrared Drying kinetic parameters with different drying methods.

| Variety | Drying Method | Pretreatment | Operating conditions | Drying time (h) | Effective diffusivity ($m^2/s$) | Activation energy (kJ/mol) | Reference |
|---------|---------------|--------------|----------------------|-----------------|---------------------------------|----------------------------|-----------|
| Ning Qi 1 | HAD | - | 50°C, RH20%, 2 m/s | 24 | $1.04 \times 10^{-8}$ | 48.37 | 93 |
| Ning Qi 7 | HAD | soaked in sodium carbonate solution (30 g/kg), 1 min | 40°C | 27 | $5.00 \times 10^{-11}$ | 49.65 | 94 |
| Ning Qi 1 | HAD | - | 50°C | 50 | $8.94 \times 10^{-11}$ | - | 95 |
| Ning Qi 7 | HAD | soaked in sodium carbonate solution (30 g/kg), 1 min | 52°C-64°C, 60%-10% | 32 | - | - | 62 |
| Ning Qi 5 | FIRD | soaked in sodium carbonate solution (0.4%) | 70°C, irradiation height | 13 | $0.87 \times 10^{-7}$ | - | 96 |
| Ning Qi 1 | MD | soaked in sodium carbonate solution | Pulse ratio 1.67, microwave power 185 W | 9 | $5.28 \times 10^{-11}$ | 54.78 | 97 |
Table 2. Variation of quality of *Lycium barbarum* with different drying methods.

| Variety | Drying Method | Pretreatment | Dry Conditions | L | a | b | ΔE | Reference |
|---------|---------------|--------------|----------------|---|---|---|----|-----------|
| Ning    | HAD           | fresh        | -              | 25.97 ± 0.12a | 17.30 ± 0.15a | -  | 93 |
| Qi 1    | 50°C, RH20%, 2 m/s | - | 23.11 ± 0.09b | 11.03 ± 0.11b | 10.87 |
|         | 60°C, RH20%, 2 m/s | - | 22.79 ± 0.05c | 10.67 ± 0.07c | 13.01 |
|         | 70°C, RH20%, 2 m/s | - | 21.99 ± 0.06d | 9.62 ± 0.05d | 13.91 |
| Ning    | HAD           | fresh        | -              | 47.18 ± 0.12a | 18.96 ± 0.76a | 0a  | 94 |
| Qi 7    | 40°C          | -            | 40.65 ± 0.21b | 12.49 ± 1.02c | 16.45 ± 0.54c |
|         | 50°C          | -            | 38.88 ± 0.88c | 10.42 ± 0.55de | 21.02 ± 0.19d |
|         | 60°C          | -            | 36.90 ± 0.53d | 8.29 ± 1.02g | 27.78 ± 2.11e |
|         | 40°C          | soaked in sodium carbonate solution (30 g/kg) | 40.98 ± 1.17b | 14.90 ± 0.01b | 12.67 ± 0.33b |
|         | 50°C          | -            | 40.86 ± 0.36b | 11.99 ± 0.50cd | 16.48 ± 0.34c |
|         | 60°C          | -            | 37.30 ± 0.21d | 9.22 ± 1.29ef | 25.69 ± 2.42e |
| Ning    | FIRD          | fresh        | -              | 39.48b | 20.396 | 7.3467 |
| Qi 5    | 30% sucrose solution permeated | - | 37.566 | 19.402 | 7.8661 |
|         | 40 KHz, 60°C by ultrasound | - | 37.354 | 19.132 | 7.8661 |
|         | 40 KHz, 60°C by ultrasound+Hot scalding with distilled water at 100°C | - | 37.700 | 20.588 | 6.7564 |
|         | 40 KHz, 60°C by ultrasound+30% sucrose solution permeated | - | 37.236 | 17.901 | 9.1708 |
|         | 70°C, irradiation height 210 mm | - | 35.978 | 18.136 | 9.1185 |
|         | 40 KHz, 60°C by ultrasound+Hot scalding with distilled water at 100°C | - | 40.216 | 21.358 | 5.8519 |
| Ning    | Natural drying | soaked in sodium carbonate solution (5%) | - | 24.46 ± 1.36 | 19.72 ± 2.61 | 100 |
| Qi 5    | Coal burning drying house | - | 30.08 ± 0.45 | 17.43 ± 1.97 |
|         | Solar energy equipment fresh | - | 35.97 ± 1.82 | 17.11 ± 1.46 |
|         | Natural drying | 40°C | 47.55 ± 0.20 | 55.13 ± 2.23 |

Different letters in the same cultivar indicate significant differences (P < 0.05).
Acknowledgments

The study was supported by Natural science foundation of Hebei Province (C2019208315), and also funded by Science and Technology Project of Hebei Education Department [BJ2021004]. Chaojing Cui, Dandan Zhao, Jin Huang and Jianxiong Hao declare that they have no conflict of interest.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Hebei Natural Science Foundation of Hebei Province [C2019208315], Science and Technology Project of Hebei Education Department [BJ2021004], and National Natural Science Foundation of China [32101878]..

References

[1] Zhong, Y.; Shahidi, F.; Naczk, M. Phytochemicals and Health Benefits of Goji Berries. Dried Fruits Phytochem Heal Eff. 2013, 133–144. DOI: 10.1002/9781118464663.ch6.
[2] Bucheli, P.; Gao, Q.; Redgwell, R.; Vidal, K.; Zhang, W. Biomolecular and Clinical Aspects of Chinese Wolfberry. Med Biol Clin Asp. 2011, 1–17. DOI: 10.1201/b10787-15.
[3] Liu, Y.; Wang, Z.; Zhang, J., and Evidence, C. Dietary Chinese Herbs. Springer, Vienna. 2015, 425–430. DOI: 10.1007/978-3-211-99448-1_48.
[4] Wang, C. C.; Chang, S. C.; Inbaraj, B. S.; Chen, B. H. Isolation of Carotenoids, Flavonoids and Polysaccharides from Lycium Barbarum L And Evaluation of Antioxidant Activity. Food Chem. 2010, 120, 184–192. DOI: 10.1016/j.foodchem.2009.10.005.
[5] Raymond Chuen-Chung SK-F. C. 2015, Springer Netherlands: Lycium Barbarum and Human Health.
[6] Inbaraj, B. S.; Lu, H.; Hung, C. F.; Wu, W.B.; Lin, C.L.; Chen, B.H. Determination of Carotenoids and Their Esters in Fruits of Lycium Barbarum Linnaeus by HPLC-DAD-APCI-MS. J. Pharm. Biomed. Anal. 2008, 47, 812–818. DOI: 10.1016/j.jpba.2008.04.001.
[7] Kulczyński, B.; Gramza-Michalowska, A. Goji Berry (Lycium Barbarum): Composition and Health Effects - A Review. Polish J. Food Nutr. Sci. 2016, 66, 67–75. DOI: 10.1515/pjfns-2015-0040.
[8] Adams, M.; Wiedenmann, M.; Tittel, G.; Bauer, R. HPLC-MS Trace Analysis of Atropine in Lycium Barbarum Berries. Phytochem. Anal. 2006, 17, 279–283. DOI: 10.1002/ pca.915.
[9] Yao, X.; Peng, Y.; Xu, L. J.; Li, L.; Wu, Q.L.; Xiao, P.G. Phytochemical and Biological Studies of Lycium Medicinal Plants. Chem. Biodivers. 2011, 8, 976–1010.
[10] Hiserodt, R. D.; Adedeji, J.; John, T. V.; Dewis, M. L. Identification of Monomethyl Succinate, Monomethyl Glutarate, and Dimethyl Glutarate in Nature by High Performance Liquid Chromatography-tandem Mass Spectrometry. Journal of Agricultural and Food Chemistry. 2004, 52(11), 3536–3541. DOI: 10.1021/jf049798m.
[11] Mikulic-Petkovsek, M.; Schmitzer, V.; Schmitzer, F.; Veberic, R. Composition of Sugars, Organic Acids, and Total Phenolics in 25 Wild or Cultivated Berry Species. J. Food Sci. 2012, 77, DOI: 10.1111/j.1750-3841.2012.02896.x.
[12] Cui, G.; Jing, L.; Feng, Q.; Xiao, Y.; Puthreti, R. Anti-hyperglycemic Activity of a Polysaccharide Fraction from Lycium Barbarum. African J Biomed Res. 2010, 13, 55–59.
[13] Pai, P. G.; Habeeba, P. U.; Ullal, S.; Ahsan, S.P.; Ramya. Evaluation of Hypolipidemic Effects of Lycium Barbarum (Goji Berry) in a Murine Model. J Nat Remedies. 2013, 13, 4–8. DOI: 10.18311/jnr/2013/110.
[14] Tang, W. M.; Chan, E.; Kwok, C. Y.; Lee, Y.; Wu, J.H.; Wan, C.W.; Chan, R.Y.K.; Yu, P.H.Fu.; Chan, S.W.A. A Review of the Anticancer and Immunomodulatory Effects of Lycium Barbarum Fruit. Inflammopharmacology. 2012, 20, 307–314. DOI: 10.1007/s10787-011-0107-3.
[15] Ni, T.; Wei, G.; Yin, X.; Liu, X.; Liu. Neuroprotective Effect of Lycium Barbarum on Retina of Royal College of Surgeons (RCS) Rats. Folia Neuropathol 2013, 51, 158–163. DOI: 10.5114/fn.2013.35959.
[16] Luo, Q.; Cai, Y.; Yan, J.; Sun, M.; Corke, H. Hypoglycemic and Hypolipidemic Effects and Antioxidant Activity of Fruit Extracts from Lycium Barbarum. Life Sci. 2004, 76, 137–149. DOI: 10.1016/j.lfs.2004.04.056.
[17] Yin, G.; Dang, Y. Optimization of Extraction Technology of the Lycium Barbarum Polysaccharides by Box-Behhken Statistical Design. Carbohydr. Polym. 2008, 74, 603–610. DOI: 10.1016/j.carbpol.2008.04.025.
[18] Fan, X. J.; Zhang, B.; Yan, H.; Feng, J. T.; Ma, Z. Q., and Zhang, X. Effect of lotus leaf extract incorporated composite coating on the postharvest quality of fresh goji (Lycium barbarum L.) fruit. Postharvest Biology and Technology. 2019, 148, 132–140. DOI: 10.1016/j.postharvbio.2018.10.020.
[19] Lewicki, P. P.; Design of Hot Air Drying for Better Foods. Trends Food Sci. Technol. 2006, 17, 153–163.
[20] Esmaili, M.; Sotudeh-Gharebagh, R.; Cronin, K.; Mousav, M.; Rezaadeh, M. Grape Drying: A Review. Food Rev. Int. 2007, 23, 257–280. DOI: 10.1080/07559120701483353.

[21] Duizer, L.: A Review of Acoustic Research for Studying the Sensory Perception of Crisp, Crunchy and Crackly Textures. Trends Food Sci. Technol. 2001, 12, 17–24.

[22] Cohen, J. S.; Yang, T. C. S. Progress in Food Dehydration. Trends Food Sci. Technol. 1995, 6, 20–25.

[23] Nep, E. I.; Conway, B. R. Physicochemical Characterization of Grewia Polysaccharide Gum: Effect of Drying Method. Carbohydr. Polym. 2011, 84, 446–453. DOI: 10.1016/j.carbpol.2010.12.005.

[24] Albanese, D.; Cinquanta, L.; Cuccurullo, G.; Di Matteo, M. Effects of Microwave and Hot-air Drying Methods on Colour, β-carotene and Radical Scavenging Activity of Apricots. Int. J. Food Sci. Technol. 2013, 48, 1327–1333. DOI: 10.1111/j.ifs.12095.

[25] Carnés, J.; De Larramendi, C. H.; Ferrer, A.; Huertas, A.J.; López-Matas, M.A.; Pagán, J.A.; Navarro, L.A.; Garcia-Abujeta, J.L.; Vicario, S.; Péa, M. Recently Introduced Foods as New Allergenic Sources: Sensitisation to Goji Berries (Lycium Barbarum). Food Chem. 2013, 137, 130–135. DOI: 10.1016/j.foodchem.2012.10.005.

[26] Wu, Z.; Li, W.; Zhao, L.; Shi, J.; Liu, Q. Drying Characteristics and Product Quality of Lycium Barbarum under Stages-varying Temperatures Drying Process. Nongye Gongcheng Xuebao/Transactions Chinese Soc Agric Eng 2015, 31, 287–293. DOI: 10.11975/j.1002-6819.2015.11.041.

[27] Carranza-Concha, J.; Benlloch, M.; Camacho, M. M.; Martínez-Navarrete, N. Effects of Drying and Pretreatment on the Nutritional and Functional Quality of Raisins. Food Bioprod. Process. 2012, 90, 243–248. DOI: 10.1016/j.fbp.2011.04.002.

[28] Zhao, Q.; Dong, B.; Chen, J.; Zhao, B.; Wang, X.; Zha, S.; Wang, Y.; Zhang, J.; Wang, Y. Effect of Drying Methods on Physicochemical Properties and Antioxidant Activities of Wolfberry (Lycium Barbarum) Polysaccharide. Carbohydr. Polym. 2015, 127, 176–181. DOI: 10.1016/j.carbpol.2015.03.041.

[29] Yang, M.; Ding, C. Electrohydrodynamic (EHD) Drying of the Chinese Wolfberry Fruits. Springerplus. 2016, 5, 1–20. DOI: 10.1186/s40064-016-2546-1.

[30] Lecas, M.; Brillouet, J.-M. Cell Wall Composition of Grape Berry Skins. Phytochemistry. 1994, 35, 1241–1243. DOI: 10.1016/S0031-9422(00)94828-3.

[31] Karathanos, V. T.; Belessiotis, V. G. Sun and Artificial Air Drying Kinetics of Some Agricultural Products. J. Food Eng. 1997, 31, 35–46. DOI: 10.1016/S0260-8774(96)00050-7.

[32] Adiletta, G.; Rizvi Alam, M.; Cinquanta, L.; Russo, P.; Matteo, M.D. Effect of Abrasive Pretreatment on Hot Dried Goji Berry. Chem. Eng. Trans. 2015, 44, x–x DOI: 10.3301/CET1544022.

[33] Ai, Y.; Jing, D. U.; Chun, L. I.; Li, W. Study on Component and Microscopic Structure of Wax of Lycium Barbarum L. 1976, 112–114. DOI: 10.13386/j.0002-0306.2011.12.035.

[34] Kök SC, D.; 2004 Determination of Characteristics of Grape Berry Skin in Some Table Grape Cultivars (VVinifera L.), 141–146

[35] Di Matteo, M.; Cinquanta, L.; Galiero, G.; Crescittelli, S. Effect of a Novel Physical Pretreatment Process on the Drying Kinetics of Seedless Grapes. J. Food Eng. 2000, 46, 83–89. DOI: 10.1016/S0260-8774(00)00071-6.

[36] Cinquanta, L.; Di Matteo, M.; Esti, M. Physical Pre-treatment of Plums (Prunus Domestica). Part 2. Effect on the Quality Characteristics of Different Prune Cultivars. Food Chem. 2002, 79, 233–238. DOI: 10.1016/S0030-8814(02)00138-3.

[37] Femenia, A.; Sánchez, E. S.; Simal, S.; Rosselló, C. Effects of Drying Pretreatments on the Cell Wall Composition of Grape Tissues. J. Agric. Food Chem. 1998, 46, 271–276. DOI: 10.1021/jf9705025.

[38] Rocha, T.; Lebert, A.; Marty-Audouin, C. Effect of Pretreatments and Drying Conditions on Drying Rate and Colour Retention of Basil (Ocimum Basilicum). LWT - Food Sci. Technol. 1993, 26, 456–463. DOI: 10.1016/s0023-6438(93)90038-3.

[39] Toğrul, I. T.; Pehlivan, D. Modelling of Thin Layer Drying Kinetics of Some Fruits under Open-air Sun Drying Process. J. Food Eng. 2004, 65, 413–425. DOI: 10.1016/j.jfoodeng.2004.02.001.

[40] Amagase, H.; Farisworth, N. R. A Review of Botanical Characteristics, Phytochemistry, Clinical Relevance in Efficacy and Safety of Lycium Barbarum Fruit (Goji). Food Res. Int. 2011, 44, 1702–1717. DOI: 10.1016/j.foodres.2011.03.027.

[41] Liu, M.; Wang, S., and Li, K. Study of the Solar Energy Drying Device and Its Application in Traditional Chinese Medicine in Drying. Int J Clin Med. 2015, 6, 271–280.

[42] Guowei, R.; Huiyuan, Z.; Guo Xuexia, Y. S. Design and Testing of Solar Dryer for Chinese Wolfberry Using Temperature and Humidity by Stages Changed Hot-air Method. Packag Food Mach. 2015, 33(6), 34–38.

[43] Song, M.; Guo Xuedong, G. Z. S. The Application of Solar Drying in Processing Chinese Wolfberry. Agric Equip Technol. 2008, 34(5), 27–29.

[44] Doymaz, I.; Pretreatment Effect on Sun Drying of Mulberry Fruits (Morus Alba L.). J. Food Eng. 2004, 65, 205–209. DOI: 10.1016/j.jfoodeng.2004.01.016.

[45] Sagar, V. R.; Suresh Kumar, P. Recent Advances in Drying and Dehydration of Fruits and Vegetables: A Review. J. Food Sci. Technol. 2010, 47, 15–26.

[46] Ratti, C.: Hot Air and Freeze-drying of High-value Foods: A Review. J. Food Eng. 2001, 49, 311–319. DOI: 10.1016/S0260-8774(00)00228-4.

[47] Varanlis, A. I.; Brennan, J. G.; MacDougall, D. B. Proposed Mechanism of High Temperature Puffing of Potato. Part II. Influence of Blanching and Initial Drying on the Permeability of the Partially Dried Layer to Water Vapour. J. Food Eng. 2001, 48, 369–378. DOI: 10.1016/S0260-8774(00)00198-9.
[48] Qinghua, J.; Shijie, Z.; Jingfu, C.; Zhicheng, X. Hot Air Drying Characteristics of Chinese Wolfberry. J Agric Mech Res. 2010, 6, 153–157. DOI: 10.13427/j.cnki.njvji.2010.06.036.

[49] Maskan, M.; Drying. Shrinkage and Rehydration Characteristics of Kiwifruits during Hot Air and Microwave Drying. J. Food Eng. 2001, 48, 177–182. DOI: 10.1016/S0260-8774(00)00155-2.

[50] Peng, H.; Yin, Y.; Tang, J. Microwave Drying of Food and Agricultural Materials: Basics and Heat and Mass Transfer Modeling. Food Eng. Rev. 2012, 4, 89–106.

[51] Maskan, M.; Kinetics of Colour Change of Kiwifruits during Hot Air and Microwave Drying. J. Food Eng. 2001, 48, 169–175. DOI: 10.1016/S0260-8774(00)00154-0.

[52] Maskan, M.; Microwave/air and Microwave (R) Nish Drying of Banana. J. Food Eng. 2000, 44, 71–78.

[53] Prabhanjan, D. G.; Ramaswamy, H. S.; Raghavan, G. S. V. Microwave-assisted Convective Air Drying of Thin Layer Carrots. J. Food Eng. 1995, 25, 283–293. DOI: 10.1016/0260-8774(94)00031-4.

[54] Yongsawatdigul, J.; Gunasekaran, S. Microwave-vacuum Drying of Cranberries: Part IIQuality Evaluation. J. Food Process. Preserv. 1996, 20, 145–156. DOI: 10.1111/j.1745-4549.1996.tb00851.x.

[55] Sarimveis, A.; Microwave Drying Characteristics of Coriander (Coriandrum Sativum L.) Leaves. Energy Convers. Manag. 2011, 52, 1449–1453. DOI: 10.1016/j.enconman.2010.10.007.

[56] Lingjiang, M.; Song, M.; Mingbin, L.; Yanchang, W.; Pengyue, M. Microwave Drying Characteristics of Chinese Wolfberry and the Effect on the Quality of Chinese Wolfberry. J Agric Mech Res. 2015, 5, 208–211. DOI: 10.13427/j.cnki.njvji.2015.05.046.

[57] Salazar-González, C.; Martín-González, M. F. S.; López-Malo, A.; Sosa-Morales, M. E. Recent Studies Related to Microwave Processing of Fluid Foods. Food Bioprocess Technol. 2012, 5, 31–46.

[58] Chandrasekaran, S.; Ramanathan, S.; Basak, T. Microwave Food processing - A Review. Food Res. Int. 2013, 52, 243–261.

[59] Chua, K. J.; Chou, S. K.; Ho, J. C.; Hawlader, M. N. A. Heat Pump Drying: Recent Developments and Future Trends. Dry. Technol. 2002, 20, 1579–1610. DOI: 10.1081/DRT-120014053.

[60] Chua, K. J.; Chou, S. K.; Yang, W. M. Advances in Heat Pump Systems: A Review. Appl. Energy. 2010, 87, 3611–3624.

[61] Prasertsan, S.; Saen-saby, P. Heat Pump Drying of Agricultural Materials. Dry. Technol. 1998, 16, 235–250. DOI: 10.1080/073739808917401.

[62] Zhao, D.; Peng, Y.; Li, M.; Ni, Y. Design and Application of Wolfberry Heat Pump Drying System. Trans Chin Soc Agric Eng. March 2016, 359–365. 10.6041/j.1000-1298.2016.S0.055.

[63] Colak, N.; Hepbasli, A. A Review of Heat Pump Drying: Part 1 - Systems, Models and Studies. Energy Convers. Manag. 2009, 50, 2180–2186. DOI: 10.1016/j.enconman.2009.04.031.

[64] Oikonomopoulou, V. P.; Krokida, M. K.; Karathanos, V. T. The Influence of Freeze Drying Conditions on Microstructural Changes of Food Products. Procedia Food Sci. 2011, 1, 647–654. DOI: 10.1016/j.profs.2011.09.097.

[65] Krokida, M. K.; Karathanos, V. T.; Maroulis, Z. B. Effect of Freeze-drying Conditions on Shrinkage and Porosity of Dehydrated Agricultural Products. J. Food Eng. 1998, 35, 369–380. DOI: 10.1016/S0260-8774(98)00034-1.

[66] Litvin, S.; Mannheim, C. H.; Miltz, J. Dehydration of Carrots by a Combination of Freeze Drying, Microwave Heating and Air or Vacuum Drying. J. Food Eng. 1998, 36, 103–111. DOI: 10.1016/S0260-8774(98)00054-5.

[67] Oikonomopoulou, V. P.; Krokida, M. K.; Karathanos, V. T. Structural Properties of Freeze-dried Rice. J. Food Eng. 2011, 107, 326–333. DOI: 10.1016/j.jfoodeng.2011.07.009.

[68] Marques, L. G.; Prado, M. M.; Freire, J. T. Rehydration Characteristics of Freeze-dried Tropical Fruits. LWT - Food Sci. Technol. 2009, 42, 1237–1237. DOI: 10.1016/j.lwt.2009.02.012.

[69] Chassaing, A.; Komes, D.; Bušić, A., and Belščak-cvitanić, A. Preservation of Polyphenolic Antioxidants from Goji Berries (Lycium Barbarum L.) Affected by Different Drying Techniques; Univesiti Kebangsaan Malaysia: Int Conf Food Prop, 2014.

[70] Donno, D.; Mellano, M. G.; Raimondo, E.; Beccaro, G.L.; Prgomet, Z.; Cerutti, A.K. Influence of Applied Drying Methods on Phychochemical Composition in Fresh and Dried Goji Fruits by HPLC Fingerprint. Eur. Food Res. Technol. 2016, 242, 1961–1974. DOI: 10.1007/s00217-016-2695-z.

[71] Michalczyk, M.; MacUra, R.; Matuszak, I. The Effect of Air-drying, Freeze-drying and Storage on the Quality and Antioxidant Activity of Some Selected Berries. J. Food Process. Preserv. 2009, 33, 11–21. DOI: 10.1111/j.1745-4549.2008.00232.x.

[72] Xie, L.; Zheng, Z.A.; Mujumdar, A.S.; Fang, X.M.; Wang, J.; Zhang, Q.; Ma, Q.; Xiao, H.W.; Liu, H.Y.; Goa, Z.J. Pulsed Vacuum Drying (PVD) of Wolfberry: Drying Kinetics and Quality Attributes. Dry. Technol. 2018, 36(12), 1501–1514. DOI: 10.1080/07393977.2017.1414055.

[73] Xie, Y.; Gao, Z.; Liu, Y.; Xiao, H. Pulsed Vacuum Drying of Rhizoma Dioscoreae Slices. LWT - Food Sci Technol 2017, 80, 237–249. DOI: 10.1016/j.lwt.2017.02.016.

[74] Xu, P.; Peng, X.; Yang, J.; Li, X.; Zhang, H.; Jia, X.; Liu, Y.; Wang, Z.; Zhang, Z. Effect of Vacuum Drying and Pulsed Vacuum Drying on Drying Kinetics and Quality of Bitter Orange (Citrus Aurantium L.) Slices. J. Food Process. Preserv. 2021, 0, e16098. DOI: 10.1111/jcpp.16098.

[75] Liu, Z.; Xie, L.; Zielinskiška, M.; Pan, Z.; Wang, J.; Deng, L.; Wang, H.; Xiao, H. Pulsed Vacuum Drying Enhances Drying of Blueberry by Altering Micro-, Ultrastructure and Water Status and Distribution. LWT - Food Sci Technol. 2021, 142(8), 111013. DOI: 10.1016/j.lwt.2021.111013.
[76] Riadh, M. H.; Ahmad, S. A. B.; Marhaban, M. H.; Soh., A.C.: Infrared Heating in Food Drying: An Overview. Dry. Technol. 2015, 33, 322–335. DOI: 10.1080/07373937.2014.951124.

[77] Grzdelishvili, G.; Hoffman, P. Infrared Drying of Food Products. Czech Tech Univ Prague, Dep Process Eng. 2012.

[78] Toğrul, H.: Simple of Infrared Drying of Fresh Apple Slices. J. Food Eng. 2005, 71, 311–323.

[79] Niamnuy, C.; Nachaisin, M.; Poomsa-Ad, N.; Devahastin, S. Kinetic Modelling of Drying and Conversion/degradation of Isolavones during Infrared Drying of Soybean. Food Chem. 2012, 133, 946–952. DOI: 10.1016/j.foodchem.2012.02.010.

[80] Reyes, A.; Vega, R.; Bustos, R.; Araneda, C. Effect of Processing Conditions on Drying Kinetics and Particle Microstructure of Carrot. Dry. Technol. 2008, 26, 1272–1285. DOI: 10.1080/07373930802307282.

[81] Likitratthanaporn, C.; Noonhorm, A. Effects of Simultaneous Parboiling and Drying by Infrared Radiation Heating on Parboiled Rice Quality. Dry. Technol. 2011, 29, 1066–1075. DOI: 10.1080/07373937.2011.566967.

[82] Shi, J.; Pan, Z.; McHugh, T. H.; Wood, D.; Hirschberg, E.; Olson, D. Drying and Quality Characteristics of Fresh and Sugar-infused Blueberries Dried with Infrared Radiation Heating. LWT - Food Sci. Technol. 2008, 41, 1962–1972. DOI: 10.1016/j.lwt.2008.01.003.

[83] Adak, N.; Heybeli, N.; Ertekin, C. Infrared Drying of Strawberry. Food Chem. 2017, 219, 109–116. DOI: 10.1016/j.foodchem.2016.09.103.

[84] Sui, Y.; Yang, J.; Ye, Q.; Li, H.; Wang, H. Infrared, Convective, and Sequential Infrared and Convective Drying of Wine Grape Pomace. Dry. Technol. 2014, 32, 686–694. DOI: 10.1080/07373937.2013.853670.

[85] Xie, L.; Mujumdar, A. S.; Fang, X. M.; Wang, J.; Dai, J. W.; Du, Z. L.; Xiao, H. W.; Liu, Y. H.; Gao, Z. J. Far-infrared Radiation Heating Assisted Pulsed Vacuum Drying (FIR-PVD) of Wolfberry (Lycium Barbarum L.): Effects on Drying Kinetics and Quality Attributes. Food Bioprod. Process. 2017, 102, 320–331. DOI: 10.1016/j.fbp.2017.01.012.

[86] Xie, L.; Mujumdar, A. S.; Zhang, Q.; Wang, J.; Liu, S. X.; Deng, L. Z.; Wang, D.; Xiao, H. W.; Liu, Y. H.; Gao, Z. J. Pulsed Vacuum Drying of Wolfberry: Effects of Infrared Radiation Heating and Electronic Panel Contact Heating Methods on Drying Kinetics, Color Profile, and Volatile Compounds. Dry. Technol. 2017, 35, 1312–1326. DOI: 10.1080/07373937.2017.1319854.

[87] Cho, S.; Shin, M. H.; Kim, Y. K.; Seo, J. E.; Lee, Y. M.; Parli, C. H.; Chung, H. J. Effects of Infrared Radiation and Heat on Human Skin Aging in Vivo. J Investig Dermatol Symp Proc 2009, 14, 15–19. DOI: 10.1038/jidsympproceedings.2009.7.

[88] Esehaghbeigi, A.; Basiry, M. Electrohydrodynamic (EHD) Drying of Tomato Slices (Lycopersicon Esculentum). J. Food Eng. 2011, 104, 628–631. DOI: 10.1016/j.jfoodeng.2011.01.032.

[89] Ding, C. J.; Lu, J.; Song, Z. Q. Electrohydrodynamic Drying of Carrot Slices. PLoS ONE. 2015, 10(4), e0124077. DOI: 10.1371/journal.pone.0124077.

[90] Bai, Y. X.; Qu, M.; Quan, L. Z.; Li, X. J.; Yang, Y. X. Electrohydrodynamic Drying of Sea Cucumber (Stichopus Japonicus). LWT-Food Sci. Technol. (54), 570–576, 2013. DOI: 10.1016/j.lwt.2013.06.026.

[91] Chen, Y.; Martyenko, A. Combination of Hydrothermodynamic (HTD) Processing and Di_reent Drying Methods for Natural Blueberry Leather. LWT-Food Sci. Technol. 2018, 87, 470–477. DOI: 10.1016/j.lwt.2017.09.030.

[92] Ni, J.; Ding, C.; Zhang, Y.; Song, Z.; Hu, X.; Hao, T. (2019) Electrohydrodynamic Drying of Chinese Wolfberry in a Multiple Needle-to-plate Electrode System. Foods (Basel, Switzerland) 8: 152. doi: 10.3390/foods8010152.

[93] Batau, H. S.; Kadakal, E. Drying Characteristics and Degradation Kinetics in Some Parameters of Goji Berry (Lycium Barbarum L.) Fruit during Hot Air Drying. J Italian J Food Sci. 2021, 33(1), 16–28. DOI: 10.1585/ijfs.v33i1.1949.

[94] Zhao, D.; Chen, D.; Peng, Y.; Wang, Y.; Zhang, Z.; Ni, Y. Kinetic Model and quality Analysis of Hot Air Drying Process of Lycium Barbarum. J. Chin. Inst. Sci. Food. 2017, 36, 124–128. DOI: 10.16239/j.issn.1009-7848.2017.03.016.

[95] Hu, Y.; Wei, J.; Li, N.; Hu, H. Effect of Different Hot Air Drying Temperature on Drying Characteristics of Lycium Barbarum. J Food Ferment Indus, 2017, 130–134. DOI: 10.13995/j.cnki.11-1802/s.201701022.

[96] Fan, F.; Luo, Y.; Li, W.; Wei, B.; Huang, X. Effect of Different Pretreatment Methods on Far-infrared Drying Characteristics and Polysaccharides of Lycium Barbarum. J Chin Traditional Herbal Drugs.2020, 51(16), 4183–4190. DOI: 10.7501/j.0253-2670.2020.16.011.

[97] Wang, H.; Mu, S.; Wu, J.; Xie, Y. X.; Chen, X. M.; Liu, S. S. Application and Modeling Microwave Drying of Chinese Wolfberry Based on Weibull Distribution. J Modern Food Science Technol. 2018, 34, 141–147. DOI: 10.13982/j.mfst.1673-9078.2018.1.022.

[98] Song, H.; Chen, Q.; Bi, J.; Zhou, L.; Yi, J. Effects of Different Drying Methods and Alkali Pretreatment on Drying Characteristics and Quality of Fresh Goji Berries (Lycium Barbarum). J Food Sci. 2018, 80(15), 207–216. DOI: 10.7506/spks1002-6630-201815029.

[99] Li, Q., and Tang, H. Quality Comparison between Freeze-drying and Hot-air Drying of Lycii. Fructus J Anhui Agri Sci. 2010, 38(26), 14779–14780. DOI: 10.3969/j.issn.0517-6611.2010.26.217.

[100] Wang, H.; Gao, Y.; Wang, J.; Yao, S.; Wang, W.; Ran, G.; Liu, Y.; Guo, X.; Zhang, H. Appropriate Drying Method to Improve the Quality of Dried Lycium Barbarum. J Trans Chin Soc Agric Eng. 2015, 31, 271–276. DOI: 10.11975/j.1002-6819.2015.21.036.

[101] Zhao, D.; Wei, J.; Hao, J.; Han, X.; Ding, S.; Yang, L. Effect of Sodium Carbonate Solution Pretreatment on Drying Kinetics, Antioxidant Capacity Changes, and Final Quality of Wolfberry (Lycium Barbarum) during Drying. J Lebensmittel Wissenschaft Und Technologie 2019, 99, 254–261. DOI: 10.1016/j.lwt.2018.09.066.