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An extensive investigation of combined freeze-drying technologies for fruit conservation

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Abstract

Drying is one of the oldest methods for preserving perishable foods and protecting fruits from microbial degradation, thereby extending shelf life. However, the bland taste and hard texture affect the marketability. This has led to the development of novel drying technologies in which, freeze-drying is one such non-thermal dehydration technique that offers benefits such as maintaining structure, texture, colour, rehydration rate and nutritional quality. Freeze-drying operates below the triple point, using temperature and pressure to remove water via vapour concentration gradients, carefully balancing critical and eutectic temperatures to preserve the structure and prevent shrinkage. Despite these advantages, freeze-drying has notable drawbacks, including high processing time, production costs and energy consumption making the technique less feasible. Several combination drying techniques have been implemented as pre- and post-treatments to address these issues, resulting in lower power consumption, cost efficiency and good quality retention. Techniques such as infrared, microwave, ultrasound and pulsed electric fields have been applied as pre-treatments or to support conventional freeze-drying processes. When combined with other techniques, freeze-drying can achieve greater energy, time and cost savings. The review presents comparative studies highlighting these benefits and discusses how these techniques can align with sustainable food processing strategies by significantly reducing energy requirements.

Keywords

combination drying techniques; drying time; energy consumption; freeze-drying; fruit preservation

Introduction

Over the past 40 years, several research studies and field investigations have revealed that 40-50% of horticulture crops planted in developing nations go to waste earlier than they can be consumed. Reduced market value or nutritional loss (such as the loss of vitamins, antioxidants and health-promoting substances) is a serious problem with fresh produce. High rates of bruising, water loss and eventual decay due to poor postharvest handling are the main causes. Fresh fruit quality is influenced by several different factors and when these factors combine, they hasten deterioration and spoiling. Drying is a crucial unit process and maybe the earliest method of food preservation (1).

The primary objective of drying is to preserve products by removing moisture, thereby inhibiting microbial degradation and transforming the material into powders, flakes, or solids with minimal alteration to its physicochemical properties (2). Drying after chemical pre-treatment has improved the shelf life with slight changes in taste (2, 3). However, conventional drying techniques result in a decline in the food's chemical and physical quality, which decreases consumer approval of the product (3). Shorter drying times, higher capacities, improved process control, reduced costs and increased operational safety are all desirable characteristics of better drying systems. In addition, drying techniques must be non-polluting and low-impact. Meeting these requirements and enhancing food quality and nutrient retention are driving ongoing advancements in drying techniques (4).

Among the various thermal and non-thermal drying methods, freeze-drying demonstrates notable effectiveness in meeting key requirements for producing high-quality dried products; however, it is limited by high energy consumption and cost. To address these limitations, hybrid techniques that combine freeze-drying with complementary methods have been developed. This review examines the scientific principles underlying these integrated approaches and synthesizes recent findings that contrast hybrid methods with freeze-drying (5). By leveraging the synergistic benefits of combined techniques, these approaches aim to maintain food quality while reducing costs and processing demands. Additionally, the review discusses recent advancements in food freeze-drying that further improve efficiency and product quality.

Freeze-drying

Freeze-drying (FD), also known as lyophilization or cryodesiccation, is a drying process followed by two phases of drying i.e. sublimation (primary drying) and desorption (secondary drying). The term "lyophilization" denotes a process that creates a product fond of the dry state. Lyophilization is a dehydration process used to remove the water present in the sample by freezing initially and then the ice crystals formed in the sample are dried by sublimation with high vacuum pressure and low temperature. This type of drying process is mostly applicable to pharmaceuticals and food products or extracts that are thermolabile and those products that are unstable for longer periods in aqueous solutions (6). Even though freeze-drying and lyophilization are used to describe the same process, freeze-drying is still a more appropriate term as the initial freezing process is described, which is crucial for this drying process (7).

The principle of freeze-drying involves three stages i.e. freezing, the primary drying phase and the secondary drying phase, which comprises five key activities such as freezing, sublimation, desorption, vacuum pumping and vapour condensation (7). The process begins with sample preparation and progresses through freezing, primary and secondary drying, yielding the final dried product with the targeted moisture content. At first, the material is frozen at very low temperatures, followed by the critical sublimation phase, which gives this process another name called “sublimation drying”, during which the frozen water transforms directly into vapour without transitioning through the liquid state. Subsequently, a vacuum is applied to facilitate the sublimation process by creating low pressure within the freeze-drying chamber. The generated water vapour is then condensed back into a solid state on a condenser. Finally, any remaining bound water can be removed during desorption (8).

Freeze-drying is achieved by subjecting food material to temperature and pressure below the triple point (the point at which three phases of a pure substance can coexist in an equilibrium). The driving force for water removal during lyophilization is the concentration gradient of water vapour between the drying front and the condenser (9). During freezing, ice crystals form until the solution reaches maximum concentration. The phase separation between the solute and ice happens with further cooling. In the primary drying phase, the vapour pressure of water increases with rising temperatures. The critical temperature for amorphous substances is the collapse temperature (the point at which the product softens and loses its original structure) and for crystalline substances, it is the eutectic melt temperature (the point at which the product is at minimum melting temperature). Therefore, it is important to maintain the primary drying temperature as high as possible, while still staying below the critical temperature to reduce the formation of large ice crystals that cause shrinkage problems and destroy the structure (10).

Combined freeze-drying

The combined freeze-drying techniques are introduced to improve conventional freeze-drying methods in particular, as the drying stage is a time-intensive operation as moisture from the product must be extracted from the product's inner layers, with the primary force responsible for mass transfer being a minimal amount of vapour pressure. The process of FD involves complex and multifaceted issues that link product characteristics, changes in the product during the freezing/drying stages, mechanisms of heat and mass transfer and the quality of the final product. This requires a keen knowledge of finding methods to assist the freeze-drying in attaining lower drying times and lower energy requirements to remove the same level of moisture absorption (10, 11).

Generally, the impact of operational factors of freeze-drying including temperature, vacuum pressure and time of processing greatly plays a role in the quality preservation of bioactivity and phytochemical levels with rapid freezing, higher drying temperature and shorter drying duration (12). Also, it's important to note that the extended drying process may lead to the degradation of ascorbic acid and anthocyanin in certain food matrices. Additionally, the freezing process can cause the breakdown of cell walls, releasing bound phenols (5, 11, 12).

Consequently, an improper drying process can lead to food degradation by oxidation, colour loss and loss of nutritional properties and structural changes (shrinking, texture loss, or alteration in the food's original microstructure), all of which can make the food product undesirable to consumers. Being a widely acknowledged drying method, its adoption can be affected by its high cost and significant energy consumption resulting from the extended drying time. This limitation restricts its applicability across a broad spectrum of products in the food industry (1, 13). Combined freeze-drying, recognized as an advanced technology, combines the advantages of various drying techniques, improving the capabilities of freeze-drying alone in terms of product bioactivity, physical quality, sensory characteristics, operational time, energy efficiency and process costs (14-16). A brief illustration of combined freeze drying and its advantages is mentioned in Fig. 1.

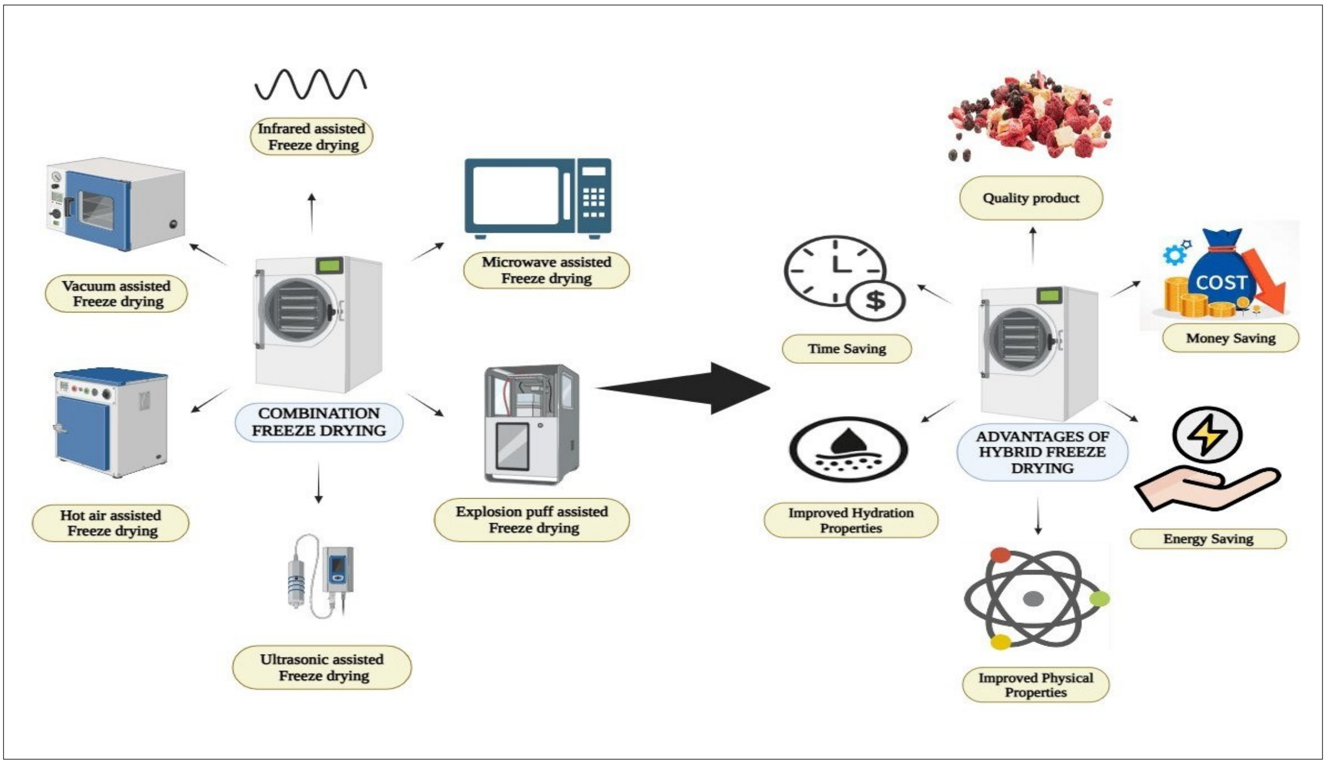

Fig. 1. Brief illustration of combined freeze drying and its advantages.

Combined freeze-drying methods for fruits

Freeze-drying is an intriguing approach for the dehydration of heat-sensitive materials, such as fruits. Studies show that freeze-drying fruits result well in retaining the minerals and vitamins in dried products along with the original flavour and aroma. The solids in a variety of fruits are in an amorphous metastable condition that is extremely responsive to variations in moisture content and temperature (17, 18). The glass transition temperature (Tg), which varies depending on the fruit used, occurs when the matrix transits from a glassy state to a rubbery state and impacts both chemical and physical changes that occur during food processing and storage. An excellent way to quantify the damage done to the material during processing and drying is to assess the rehydration ratio, which is considered to be significant in freeze-dried fruits (17).

One of the best ways to maintain product quality and reduce hygroscopicity in fruits is to pre-dry before freeze-drying and post-dry after freeze-drying (19). These days, novel methods including microwave, infrared and radiofrequency-aided freeze-drying are used to speed up the duration of drying while enhancing the final quality of dried fruits (18). To minimize the drawbacks of using freeze-drying method alone, such as a long drying time, high power consumption, or product quality, numerous combinations of drying methods have been applied. These combinations significantly reduce power consumption while ensuring superior quality and nutritional retention (20). The different combined freeze-drying methods followed in various fruits are compiled together in Table 1 given below and each combined techniques are explained technically and elaborated with some examples in upcoming headings.

Microwave-assisted freeze-drying in fruits

Microwave (MW) drying uses electromagnetic waves to produce heat inside the product. The electromagnetic waves include microwave radiation, which runs from 300 MHz to 300 GHz. Rapid internal heating results from MW's production of heat inside the food product and dry the product. When freeze-drying is combined with MW drying, microwave energy readily penetrates the ice, reducing the drying time by approximately 50% to 75% as compared to traditional FD (21). Combining microwave and FD results in a hybrid process that preserves nutrients and enhances fruit colour while increasing the drying pace and consuming less energy (22, 23). Microwave-assisted freeze drying (MAFD) is an advanced dehydration technique that combines MW heating with traditional FD, significantly reducing drying times. By providing rapid internal heating, MAFD accelerates the sublimation of ice crystals, preserving the nutritional quality, colour, texture and flavour of heat-sensitive foods. The method also offers energy savings and better retention of bioactive compounds due to lower operational temperatures and timings. Additionally, MAFD minimizes shrinkage and structural damage, resulting in a higher-quality final product. Therefore, it shows great potential for industrial-scale applications, especially for high-value fruits and vegetables (24).

Higher MW power densities also result in faster drying rates and shorter drying times. When the sample reaches 20% transition moisture content, with a drying temperature of 40°C, 8 rpm rotational speed and 6 W/g MW power density, the method works well, saving approximately 34.5% in power consumption and cutting the drying time by 33.3% for pineapples (11). When compared to FD-dried food, MAFD products exhibit higher levels of volatile retention. Although MAFD can produce dried food that is almost as high-quality as freeze-drying and even higher, many logistical challenges still need to be solved. In hybrid MW freeze-drying systems, vacuum pressure and MW power are critical determinants of product quality (23, 25).

Table 1. Overview of combination techniques for improved freeze-drying in fruits

S.No	Combined Freeze drying	Dehydration technology	Fruits used	Pre-treatment	Drying parameters	Improvements recorded	Reference
1.	**Microwave-assisted Freeze-drying**	Pulsed-Spouted Bed Microwave Freeze Drying	Apple Cuboids	Osmotic dip in 1% NaCl for 15 mins and frozen at -65°C	Frozen samples were dried at -20°C in three stages using 640-800 W microwave power, spouting frequencies of 0.5 s/5-10 min, for 45 to 315 minutes, reaching 0.09 g/g moisture.	Improved Drying time, apple colour, porosity & volatile compounds are well retained	(2)
		Microwave Freeze Drying	Apple Slices	3% citric acid solution dip and frozen at -25°C for 8h	The experiment used two microwave power schemes: first changed acc. to dielectric property (3, 2.5, 1.5 W/g for 2,2.5,1.5h) and fixed (2.5 W/g), with 60 Pa pressure and -40°C cold trap, repeated twice.	Improved drying time, colour and rehydration ratio	(67)
		Vacuum Microwave -assisted Freeze-drying	Apple Slices	Dipped in 0.5% citric acid, 0.2% NaHSo$_4$, 0.4% CaCl, 0.5% NaCl for 0.5 h, then frozen at -30°C for 2h	Apple chips after FD at with moisture contents of 5.71, 0.67, 0.43, 0.25 (d.b.) were dried using VMD at 200,300,400 W and 5,10,15 kPa vacuum pressure	Reduced drying time by 40%, improved the nutrition retention	(68)
		Pulse-Spouted Microwave Freeze Drying	Banana Cubes	Pre-cooling at 3°C/min to -40°C, 80±5 Pa pressure, and 0.1-0.6 kW microwave power	Frozen samples (100±0.5 g) were dried at 80 Pa, with microwave power at 1-3 W/g, spouting time at 2-4 seconds, and intervals of 300-900 seconds.	Shortened drying time and Improved colour & moisture level	(25)
		Pulsed fluidized bed microwave freeze-drying	strawberries	Ultrasound-assisted osmotic dehydration (OD in sugar solutions with 1% CaCl2, followed by UD at 180-360 W for 15 minutes.) And frozen at -80°C for 24 hours.	After USOD samples dried 80 ± 5 Pa, pulse for 30s/10 min at 60 °C	Improved texture, nutritional quality, and reduced drying time by 10%	(69)
		Microwave-vacuum (MWV) drying assisted freeze drying	Apple Chips	Microwave drying at 2W/g power to remove 37% moisture and frozen at -25°C for 20 min	After MVD, FD at 30°C at 0.2 kPa for 15 h	Improved vitamin C retention, colour, texture, rehydration and reduced drying time	(70)
		Microwave-assisted freeze drying	Pineapple	Samples frozen at -35 °C	The drying 4, 6, 8 W/g power under 10 kPa (reached the final moisture content in 30, 60 and 90 min) pressure for 6 hours	Reduced 33.3% of drying time and saved 34.5% power consumption	(66)
		Microwave-assisted freeze drying	Foamed Raspberry puree	Processed into seedless puree, mixed with potato protease inhibitor (2-5 - 10% for foaming, and added maltodextrin (5 - 30%) and pectin (2.5%) for stabilizing. Foam frozen at -80°C	The condenser was set to -50°C and microwave power was pulsed at 1.0, 1.5 and 2.0 W/g to maintain product surface temperature at 30°C	Higher ascorbic acid & anthocyanin retention and improved drying rate	(71)
		Pulse-spouted microwave freeze drying	Raspberry	Frozen at -80°C for 10 hours	Dried at 40°C, with a vacuum set to 80 ± 2 Pa. The temperature was reduced to -15°C before activating the microwave system	Improved drying uniformity and rate	(72)

2.	**Hot air-assisted Freeze-drying**	Freeze Vacuum Drying Combined Hot Air Drying	Kiwifruits	frozen at -40°C and FD under 20-40 Pa pressure at 20°C and condenser temperature of -60°C.	Samples are freeze vacuum dried for 10h and air dried for 2h at 70°C with 0.1 m/s air velocity	Reduced drying time and energy requirement with improved colour, bound water & microstructure.	(34)
		Hot air-assisted Freeze-drying	Apple	Hot air drying at70 & 90°C for 3 hrs and frozen at -21C in a freezing/heating chamber	The apple dried to a moisture content of 5-6% (w.b.) at an absolute pressure of 85-90 Pa at 24° C and a condenser temperature of -48°C	Reduced drying time by 36%. improved colour and firmness	(35)
		Combined hot-air freeze drying	Blueberry	Frozen at -25°C in quick freezer	Samples dried at 60°C; -20 to 20°C for 2, 3, 4 hrs with 50 Pa pressure with 1 m/s velocity	Reduced drying time, power consumption and improved rehydration qualities	(32)
3.	**Infrared-assisted freeze drying**	Sequential infrared radiation assisted freeze-drying	Strawberry	Pre-dried to remove 30%, 40% and 50% of their initial weight with IR intensities (3000, 4000, and 5000 W m-2) and frozen at -18°C	After IR drying samples FD from 1 to 22 & 29 hrs.	Improved Microstructure, Rehydration, Shrinkage and texture	(44)
		Mid-Infrared-Freeze Drying	Pear	Samples dried with 2.4 - 3.0 µm radiation and heating intensity with 3 to 5.5 kWm^{-2} at 40-70°C for 5 mins and frozen at -24 °C.	Frozen samples were dried at 23°C with 85-95 Pa pressure and condenser temperature at -47°C	Samples had darker colour, better rehydration & higher nutritional retention	(16)
		Infrared assisted freeze drying	Banana	Frozen and stored at -80°C	Samples dried under 3 conditions like IRAFD-2.7 kW/m^2, IRAFD-2.7 kW/m^2 at 20% WR, IRAFD 2.7 kW/m^2 at20% WR TO 4 kW at 0°C and FD under 267 Pa pressure and condenser temp of -100 °C	Improved crispness, colour & texture.	(39)
		Near and Mid-Infrared-assisted Freeze-drying	Blackberry	Samples stored at -75°C	Sample dried using FD at -40°C & 99.8 Pa pressure followed by NIR with 150W light, 700-1000 nm wavelength and MIR with 100 W, 1.4-3 µm	Reduced Drying time, drying cost and improved phenol, anthocyanin & rehydration with NIRFD	(42)
		Infrared assisted freeze drying	Strawberry	Samples frozen at -50°C in deep freezer for 24h.	Samples dried under conditions like IRAFD -1.6 kW/m^2,1.6 kW/m^2 at 20% WR,40% WR, 60% WR with FD at 6.67 Pa vacuum, -100°C condenser temperature	Rapid drying with less energy requirement and improved texture, microstructure & colour.	(43)
		Infrared assisted freeze drying	Apple	Infrared pre-drying with IR intensity of 5 kW for 3,4,5 mins	The apple dried to a moisture content of 5-6% (w.b.) at an absolute pressure of 85-90 Pa at 24° C and a condenser temperature of -48°C	Reduced drying time by 36%. Improved colour and firmness	(35)
		Combined infrared freeze drying	Blueberry	Frozen at -25°C in quick freezer	Samples dried with 4.5 kW/m^2 at 60°C; -20 to 20°C for 2, 3, 4 hrs with 50 Pa pressure	Reduced drying time, power consumption and improved rehydration qualities	(32)
		Vacuum infrared freeze drying	Blueberry	Stored at -65°C in cryogenic refrigerator for 12h. Pre-treated with Co_2 laser perforation for 10.64 µm wavelength at 20 kHz, 30 W & 100 mm/s, ultrasound at 45 kHz, 20W/g power for 20 min after thawing at 4°C for 5 h, freezing thawing at 4°C for 4 h	Samples after pre-treatment dried with IR radiator temperature at 60°C and FD at -40°C with 80 Pa pressure	Pretreatment improved drying time, rehydration capacity & shrinkage.	(73)

4.	**Ultra sonic-assisted freeze drying**	Ultra sonic-assisted vacuum freeze drying	Strawberry	Samples frozen atat -20°C for 48h and stored atat -40°C. Pretreated at1. ultrahigh pressure with 100 MPa for 10 mins, Ultrasound at 40 kWz, 200 W for 25 mins in 8l distilled H_2O.	Pretreated samples VFD at -50°C, 10 Pa pressure & 4° C for 20h	Reduced drying time and improved anthocyanin, flavonoid, phenolic and antioxidant activity.	(74)
		Ultrasound -assisted blanching treated freeze drying	Guava	Samples immersed in ultrasonic bath at 37 kHz, 200 W power at65°C for 5 & 10 min.	Pretreated samples dried at -40°C freezing with 40°C, 0.75 mbar pressure drying	Reduced power consumption and improved quality	(48)
		Ultrasound-assisted vacuum freeze drying	Strawberry	Sliced & soaked in 1:4 sucrose solution and into ultrasonic bath in 3 modes 1. Single-frequency mode with 20 & 40kHz, 2. Dual frequency with 20/40kHz alternatively, 3. SiDM with 20 &40 kHz at same time with 30W/L Power, 5s/5s pulse time for 30 min.	Frozen samples (-40°C) dried in VFD with dying at 25°C, 0.518 Mbar & -90°C condenser temperature.	Improved vit. C, colour, flavor, antioxidants, anthocyanins, phenols with SeDM pretreatment.	(49)
		Ultrasound assisted Atmospheric freeze drying	Apples	Samples frozen at at-18±1°C for 24h.	Frozen samples dried with 0,25,50,75W power, 1,2,4,6 m/s air velocity and -5, -10, -15°C temperatures for apple cubes of different dimensions.	Improved Drying time and power consumption	(75)
		Ultrasonically induced nucleation assisted freeze drying	Strawberry	Sample undergone ultrasonic assisted freezing with $CaCl_2$ as medium with varying temperatures (0°C, -1°C, -2°C).	Samples dried with 90 Pa pressure, 50°C & -40 to -45°C condenser temperature	Improved cell structure, texture and reduced drying time	(47)
		Ultrasound assisted atmospheric freeze drying	Orange peel	Samples dried with -10±1° C and 1 m/s velocity	Ultrasound application with 20.5 kW/m^3, 21.9 kHz	Drying time reduced by 57% and improved product quality.	(46)
		Ultrasonic assisted freeze drying	Strawberry	Ultrasonic pre-treatment: 25 kHz, 60 W, 30°C	Before Freeze-drying samples stored at -25°C for 24 hours. Freeze dried with Evaporator temperature: -40°C, Pressure: 160 Pa, for 24 h	Produced more vivid and reddish colour with better retention of organoleptic properties of the strawberries	(76)
		Ultrasound and osmotic dehydration-assisted freeze-drying	Yellow peach	Samples osmotically dehydrated in trehalose (40%, *w/v*) for 15 mins and CaLa (1%, *w/v*). Ultrasound with 20,28,40 kHz frequencies	Pretreated samples dried at 20±°C & 0,180,240,300W power.	Improved drying time, energy consumption and quality of peaches	(77)
		Ultrasound assisted Vacuum Infrared Freeze drying	Blueberry	Stored at -65°C in cryogenic refrigerator for 12h. ultrasound at 45 kHz, 20W/g power for 20 min after thawing at 4°C for 5 h,	Samples after pre-treatment dried with IR radiator temperature at 60°C and FD at -40°C with 80 Pa pressure	Pretreatment improved drying time, rehydration capacity & shrinkage.	(73)
		Ultra sonic-assisted vacuum freeze drying	Strawberry	Samples frozen at -20°C for 48h and stored at -40°C. Pretreated at1. ultrahigh pressure with 100 MPa for 10 mins, Ultrasound at 40 kWz, 200 W for 25 mins in 8l distilled h_2o .	Pretreated samples VFD at -50°C, 10 Pa pressure & 4° C for 20h	Reduced drying time and improved anthocyanin, flavonoid, phenolic and antioxidant activity.	(78)

5.	**Explosion puff-assisted freeze-drying**	Instant Controlled Pressure Drop (DIC) -Assisted Freeze Drying	Jackfruit	Samples frozen at -40°C	Sample FD at 25°C, 0.1 kPa pressure with -56 °C condenser temperature. And then equilibrated at 90°C for 10 mins with vacuum to 3kPa and then instant pressure drop to 5kPa for <0.2 s at 60°C for 2.5h	Reduced drying time, power consumption and Improved colour, texture, antioxidant activities, expansion ratio.	(53)
		Freeze drying assisted explosion puffing drying	Mango, pitaya, papaya	Samples Freeze dried at -55°C condenser temperature with 0.1 kPa pressure for 8-12 hr	Samples dried at 90°C under 3 kPa pressure. Then instant pressure drops to 5 kPa for <0.2 s. again the samples dried at 60°C for 3kPa pressure.	Improved physicochemical, texture, colour, and microstructure properties and reduced drying time.	(52)
6.	**Pulsed electric field (PEF)-assisted freeze drying**	Pulsed electric field -assisted freeze drying	Apple	Pretreated with PEF with 24 kV voltage, exponential decay for 7 µs with 0.05 s gap (20 Hz) and 240 mm electrode distance.	Samples fast frozen at -40°C for 3.5 h and slow frozen at -4, -7,-10,-12,-15,-40°C/2h. Vacuum freezing at 63 Pa pressure. Then samples FD at 20°C, 63 Pa & -25° condenser temp.	Improved drying time and physical properties	(79)
		Pulsed electric field -assisted freeze drying	Apple	Pretreated with PEF with 30 kV voltage, exponential decay for 0.5 s gap (2 Hz) for 40 ms and 280 mm electrode distance.	FD at 40 & 60°C for 0.1, 0.25, 1 mbar with -55 °C condenser temp. for 5 hr	Reduced drying time, improved macro-, microscopic & nutritional properties	(56)
		Pulsed electric field pre-treated freeze drying	Strawberry	PEF treatment with exponential decay for 0.5 s gap (2 Hz) for 40 ms (1.07 kV/cm, 1 kJ/kg specific energy input)	Samples frozen at-34°C with 2 m/s air flow. FD at25 – 130°C, 1 mbar vacuum & -45°C condenser temperature.	Improved microstructure, more uniform pore distribution, increased crunchiness and colour preservation	(80)
		Pulsed electric field assisted vacuum freeze-drying	Apple tissue	PEF treatment at 800 V/cm	Vacuum cooling & FD at 40°C, 10 mbar pressure for 5 hr	Increased rehydration capacity (~1.3), reduced shrinking, improved pore structure	(81)
		Pulsed electric field enhanced freeze-drying	Apple tissue	PEF treatment (1-2 kV/cm, 10-60 pulses)	Samples dried with Chamber pressure: 35 Pa, Heating board temp: 75°C, Condenser temp: -45°C, 7.5 hr	Shortened Drying time by 17.73%, reduced energy consumption by 24.74%, improved rehydration	(82)
		Pulsed Electric Field Pretreated Freeze drying	Apricots	Samples pre-dried with Low PEF (0.7 kV/cm), Medium PEF (1.2 kV/cm), High PEF (1.8 kV/cm)	Freeze drying at -20°C for 72 hours	Improved texture, increased antioxidant activity in samples, enhanced polyphenol extraction	(83)
7.	**Osmotic dehydration assisted Freeze-drying**	Osmotic Dehydration assisted Freeze-drying	Cranberry	Samples osmotically dehydrated in fructose (76 °B) at 1:1 ratio, 23°C for 24 h. Samples frozen at -40°C	Pre-dried samples dried with 0 – 1.3 Pa at -85°C condenser temperature, then the pressure reduced to 2.7 Pa in ~20 °C	Reduced drying time, improved quality of samples	(84)
		Consecutive Osmotic Dehydration and Freeze-Drying	Kiwi Fruit	OD with 99 % sucrose at 40, 55, 70°B & 2 – 3% NaCl. Then dried at 40, 45, 50°C for 2,3, 4 hrs.	FD with 5×10^{-3} mbar pressure, -40°C condenser temperature	Reduced drying time & nutritional loss during processing	(64)
		osmotic dehydration pre-treatment with freeze drying	Strawberry	OD with fructose, maltodextrin, maltose, and sucrose at 250 rpm with 1:10 ratio.	Samples FD at -20°C & -110°C, 10 Pa pressure	Reduced drying time, improved rehydration, texture, colour, microstructure	(63)
		Osmotic Dehydration assisted Freeze-drying	Raspberry	Two infusion treatments, dry infusion (DI) with dry additives of sucrose, citric acid, sodium bisulfite and wet infusion (WI) with aqueous humectant solutions of the same	Samples dipped in liquid nitrogen, FD at -55°C, 4 Pa pressure for 48 h	Samples showed lower deformability and higher firmness; air-dried samples had better rehydration properties, lower hygroscopicity	(65)
		Osmotic Dehydration assisted Freeze-drying	Strawberry	Osmotic solutions (25% and 50% sucrose), ultrasound pre-treatment	Freeze-drying (-40°C evaporator, 160 Pa, 24 hours)	strawberries had higher lightness, a more vivid reddish colour.	(75)
		Osmotic dehydration combined freeze drying	Pineapple	Samples immersed in 800 ml of 1% citric acid with 0, 20, 60% conc.	FD at -20°C with 0.34 mbar pressure & 30°C drying temperature for 24 h	Improved phytochemical content, colour, & quality attributes.	(85)

MAFD can be challenging to scale up in industrial applications due to issues with plasma discharge. These arise when the electric field intensity in the vacuum chamber exceeds a critical threshold, leading to energy losses and overheating in the material's dry zone, which can damage the final product. This threshold is largely determined by chamber pressure, with the lowest threshold typically found within the pressure range used in conventional freeze-drying. Additionally, MAFD becomes ineffective if MW power raises the sample temperature significantly above the triple point. Overheating during MAFD can result in substantial losses of ascorbic acid and other volatile compounds. Non-uniform heating and corona discharge remain key technical challenges limiting MAFD's feasibility (26, 27).

Pulse-spouted MW freeze-drying method is introduced to solve the above-mentioned problems in which, when MW power is significantly decreased to 2 W/g in drying bananas at a medium level of maturity have retained the same mentioned above. And also found cooked flavor in the product, when the power was exceeded to 2.2 W/g and experienced a significant structural collapse, along with an increased rehydration ratio (25). Pulsed-Spouted Bed Microwave Freeze-Drying (PSMFD) technique was used to dry apple cuboids with the drying process following a 2450 MHz MW frequency, with the sample temperature rising from -20°C to 67°C over 270 minutes. This method significantly improved drying efficiency, reducing moisture content to 0.09 g/g. Also, effectively preserved the apple's colour and volatile compounds while enhancing porosity (0.87) and hardness (350-450 kPa) while producing high-quality dried apples with better texture and appearance (28).

The structural integrity and storage stability of dried raspberry puree foam using various hydrocolloids, including potato protein (5% w/w), malto-dextrin (15% w/w) and pectin (2.5% w/w) as foaming agents, were not influenced by the stability of bioactive compounds like anthocyanin and ascorbic acid. The drying process involved freezing the raspberry samples at -80°C for 24 hours, followed by MAFD with a pulsed MW power set to 1.0 W/g, maintaining a chamber pressure of 0.1 mbar and a product temperature of 30°C (27).

The study evaluated the effects of different drying methods such as FD, FD-VMD (vacuum microwave drying), and VMD-FD on pear slices. In which, FD samples had the highest crispness and least shrinkage. FD-VMD reduced drying time, preserved colour and enhanced antioxidant properties, while VMD-FD led to structure collapse. FD-VMD was most effective for quality retention and drying efficiency (29).

The study investigated drying whole strawberries using a MAFD system with different heating rates during various drying stages. Two heating rates, 0.035 °C/min and 0.2 °C/min, were applied. Results showed that MAFD preserved about 55% of vitamin C and produced strawberries with similar quality to traditional FD (30).

Hot air-assisted freeze-drying in fruits

Drying is attained by allowing a stream of hot air to flow continuously which removes the moisture from samples and it is one of the ancient drying techniques (31). It has been stated that in comparison to FD, hybrid hot air freeze-drying of fruits greatly reduces drying time and energy consumption due to its greater average mass transfer rate (3, 31, 32). At the beginning of the hot-air-drying process, free water is rapidly removed, leading to a strong mass transfer and a quicker rate of freeze-drying (33). The combination method (FVD-AD) effectively reduced drying time by 38.22% compared to FVD alone, while maintaining a balance between quality and efficiency. The FVD-AD process achieved a product with moderate hardness (5252.71±33.53 g), improved colour and better retention of bound water and microstructure. This method was also energy-efficient, consuming less energy than FVD alone and produced odors similar to fresh kiwifruits, making it a promising technique for drying functional kiwifruit snacks (34).

The bioactivity of kedondong fruit (*Spondias dulcis*) was improved after the fruits were dried using a combination of FD and hot air drying. After freezing for six or twelve hours, the material underwent a second drying stage at 60°C using hot air. Across all freeze-drying durations, the FD-treated samples exhibited superior results in total phenol content (5.56 mg GAE/g db.), ABTS antioxidant activity (9.67 µM Trolox equivalent/100 g db.) and DPPH radical scavenging activity (216.41 mg AA/100 g db.) compared to the FD+AD product. The FD12+AD method outperformed FD6+AD, showing approximately 26%, 22% and 30% better preservation of total phenol content and ABTS and DPPH antioxidant properties (15).

Hybrid hot air-assisted freeze-drying (HA-FD) in apples reduced processing time by 27.3% and increased the drying rate. However, this method negatively impacted the quality and rehydration ratio. Despite these efficiency gains, the quality trade-offs suggest careful consideration when applying this hybrid technique (35). While this approach may reduce drying time, it led to a higher final moisture content than standard vacuum freeze-drying. Maintaining chamber pressure below the triple point requires additional vacuum pump capacity, particularly in terms of flow rate and ultimate vacuum (36).

Infrared-assisted freeze-drying in fruits

Infrared radiation is the portion of the electromagnetic spectrum between visible light and MWs. When electromagnetic radiation contacts a food surface, it alters the electrical, rotational and vibrational properties of atoms and molecules (37). Integrating infrared drying with other methods, such as FD, can accelerate the process and yield superior results with reduced energy consumption (38). Among the various combined techniques including MW, hot air drying, infrared freeze-drying is particularly promising, as it enhances product quality and expedites the drying process (39, 40).

The novel technique "infrared freeze-drying" enhances heat transfer rates by utilizing infrared radiation for ice sublimation, rather than relying on electric heating plates (40). Infrared radiation, a type of electromagnetic wave with a wavelength ranging from 0.78 to 1000 µm, offers two significant advantages including uniform heating and high energy transfer efficiency. This efficiency arises from IR radiation’s ability to penetrate the product to a certain depth, raising its internal temperature without heating the surrounding air, thereby eliminating the need for an intermediary heating medium. Compared to other drying methods, infrared drying provides a faster drying rate, preserves better colour in the final product, and can be employed as a pre-dehydration step before freeze-drying (41).

The effects of HA-FD and Infrared-Assisted Freeze-Drying (IA-FD) on apple slices revealed that the method significantly reduced power consumption and processing time by approximately 45.5% compared to traditional FD. Additionally, the method demonstrated superior results in terms of firmness, water activity, rehydration rate and colour retention (maintaining a white colour) while preserving good nutritional quality when compared to HA-FD. Infrared radiation combined with freeze-drying has also been applied to the dehydration of banana snacks (35). And when near-infrared (NIR) and mid-infrared (MIR) assisted freeze-drying was employed in blackberries, shows that the NIR-assisted freeze-drying (NIR-FD) method achieved the fastest processing time, saving 29-42.5% in power consumption. This method also preserved higher anthocyanin content, improved microstructure and resulted in a greater rehydration ratio with high nutritional content compared to MIR-assisted freeze-drying (MIR-FD) (42). Similarly, infrared-assisted freeze-drying in strawberry snacks yielded significant improvements, including faster drying kinetics, reduced processing time and power consumption, as well as notable enhancements in microstructure, colour and rehydration ratio (43).

MIR-FD was used to dehydrate pears at temperatures of 40, 50 and 60°C, each for five minutes, to evaluate the performance of this hybrid drying method. They also employed traditional FD at -24°C and 85-95 Pa absolute pressure (35). MIR-FD outperformed FD in preserving total phenolic and antioxidant activity, with increases of 16.53% and 93.63%, respectively. Due to more uniform heating and reduced drying compared to FD, the MIR-FD method produced dried pear cubes with a higher rehydration ratio (3.37) and fewer physical alterations (35).

The study on sequential infrared and freeze-drying (SIRFD) of strawberry slices found that IR drying at 4000 W/m^2 and 40% weight reduction optimized drying efficiency. SIRFD produced strawberries with better colour, higher crispness and more shrinkage than conventional FD. Pre-dehydration to 40% weight reduction reduced FD time by 42%, demonstrating significant energy-saving potential. IR drying also achieved a higher drying rate than traditional hot-air drying (44).

Ultrasonic-assisted freeze-drying in fruits

The term "ultrasonic waves" describes sound waves with frequencies ranging from 104 to 109 Hz. Cavitation is the result of alternating cycles of positive and negative ultrasonic conductivity which is necessary for the mechanism to function, a microbubble forms and contracts as a result of this cycle. When the microbubble's frequency coincides with an ultrasonic frequency, it explodes, releasing significant pressure and energy. Also, it can damage the microstructure and the cell membrane during the freezing stage. However, this process can be improved through ultrasonic atomization and the method outperforms traditional freeze-drying by providing better shape retention, smaller particle sizes, higher enzyme activity upon reconstitution and enhanced protection at high temperatures and extreme pH levels (45). The drying 4, 6 and 8 W/g power under 10 kPa pressure for 6 hours of VFD show significant differences in drying times. The drying process reaches final moisture content in 30 minutes at 8 W/g, 60 minutes at 6 W/g, and 90 minutes at 4 W/g. Higher MW power densities accelerate drying but risk overheating and uneven temperature distribution, affecting quality. Optimal drying rates with balanced quality are achieved at 4-6 W/g. At 4 and 6 W/g, there are distinct preheating, constant -rate and slow-down phases, while at 8 W/g, drying begins immediately at a constant rate (11, 45).

The ultrasound pre-treatment in vacuum infrared freeze-drying (IRFD) of deep-frozen blueberries improved the drying rate, rehydration capacity and total anthocyanin retention. It reduced shrinkage, leading to better shape retention and preserved the blueberries' nutritional quality. Additionally, FTIR spectroscopy confirmed that ultrasound did not alter the dried fruit's chemical structure, ensuring the final product's quality and integrity (11).

The quality of freeze-dried yellow peach slices by applying ultrasound-assisted osmotic dehydration (USOD) and a curing agent (calcium lactobionate, CaLa) has improved. The peach slices underwent osmotic dehydration in a trehalose solution, with varying ultrasound power levels (180 W, 240 W, 300 W) before FD and found that the USOD treatment, particularly at 240 W, significantly enhanced the quality of the dried peaches, resulting in reduced pore size, better nutrient retention, and higher total phenol and oligomeric proanthocyanidin content. The addition of CaLa further improved texture and moisture content, demonstrating the effectiveness of these pre-treatment methods (5).

The ultrasound-assisted drying of orange peel using atmospheric freeze-drying at -10°C Ultrasound application (20.5 kW/m^3) was tested and the results showed that ultrasound significantly reduced drying time, by 57% in AFD. Despite the reduction in drying time, it did not affect the alcohol-insoluble residue or water retention capacity and maintained the functional properties of the dried orange peel (46). Ultrasound-assisted freezing increased nucleation temperature and reduced the characteristic freezing time. As a result, the drying process took longer due to the formation of a finer, more uniform ice crystal structure, which improved the textural hardness of the strawberries but slightly reduced their rehydration capacity. Overall, ultrasound-assisted freezing demonstrated potential for enhancing the quality of freeze-dried strawberries by creating a more desirable microstructure (47).

The impact of ultrasound-assisted blanching (UAB) on freeze-dried guava slices, where they applied UAB at 65°C for 5 and 10 minutes and noted a significant reduction in the total polyphenol oxidase and peroxidase activities by 36% and 99.5%, respectively. This pre-treatment led to a notable decrease in total processing time and energy consumption during freeze-drying. Despite a reduction in total polyphenol content and antioxidant activity, the treatment preserved colour and reduced enzymatic browning, improving the overall quality and shelf-life of the freeze-dried guava slices (48).

Strawberry slices were freeze-dried at varying temperatures and pressures, with the drying parameters including a shelf temperature profile starting at -40°C and ending at 40°C under 0.75 mbar pressure. The results indicated that optimal freeze-drying conditions led to minimal colour changes and preserved the nutritional quality of the strawberries while optimizing freeze-drying for better quality and energy efficiency in strawberry preservation. Also, the multi-mode dual-frequency ultrasound pre-treatment on vacuum FD of strawberry slices showed the best results in vitamin-C content along with rehydration, colour, flavour, phenols anthocyanin content and also improved in shortening processing time and power consumption (49).

Explosion puff-assisted freeze-drying in fruits

Explosion puffing drying (EPD), also known as Instant Controlled Pressure Drop Texturing (DIC), is an emerging technology poised to play a significant role in the future of food processing (50). The process typically involves several key steps pre-drying the sample to reach the desired moisture content, achieving water balance, applying high-temperature steam pressure, inducing a rapid pressure drop to create a vacuum; and completing the drying process. This technique relies on thermo-mechanical effects, where the sudden pressure drops following the application of saturated steam cause auto-vaporization of volatile compounds, leading to swelling and rupture of cell walls. The rapid cooling prevents thermal degradation, making DIC ideal for heat-sensitive foods, producing products with porous microstructures, low densities and high expansion characteristics (51).

The effects of FD and EPD on the quality attributes of mango, pitaya and papaya fruit chips have been studied by comparing the FD-EPD method with the more traditional hot air drying (AD) combined with EPD (AD-EPD). The study highlighted that FD-EPD resulted in improved texture, crispness and colour retention, with a significantly lower colour difference and higher retention of physicochemical properties compared to AD-EPD. The drying parameters included pre-drying at 65°C for AD and -80°C for FD, followed by EPD at 90°C. The FD-EPD method was found to produce fruit chips with better overall quality, including a more porous structure and enhanced rehydration properties (52). Also, pre-drying methods on the physicochemical and sensory qualities of EPD jackfruit chips found that the FD-EPD combination yielded the best results, producing chips with a well-expanded honeycomb structure, higher rehydration rates, lower hardness and superior retention of nutrients like ascorbic acid, phenolic and carotenoids. The FD-EPD dried chips also exhibited better sensory qualities, suggesting it is the most effective drying method for high-quality fruit chips. The impact of explosion puffing drying on the quality of jackfruit chips, particularly focusing on the physicochemical and microstructural changes is evaluated through different pre-drying methods, including AD and FD, both aimed at reducing the moisture content to a desired level before EPD. The AD was performed at 65°C, while FD was conducted at -55°C under a vacuum of 0.1 mbar. The EPD process then applied a sudden pressure drop at 90°C. And found that pre-drying with FD followed by EPD resulted in better texture, colour retention and higher nutrient preservation compared to the AD-EPD method (53).

Pulsed electric field-assisted freeze-drying in fruits

Technology utilizing pulsed electric fields (PEF) involves brief electrical treatments lasting anywhere from a few nanoseconds to several milliseconds, with pulse electric field strengths ranging from 20-80 kV/cm to 100-300 V/cm (54). The advantage of this method is that it can be used to inactivate pathogenic and alternative microorganisms as well as quality-related enzymes at high electric fields (>20 kV/cm) while preserving or minimally altering the sensory, nutritional and health-promoting qualities of liquid food products (55). By enhancing the moisture transfer from fruit tissues to the air, PEF can raise the effective water diffusion coefficient. This permits the drying of products, at lower temperatures of 20 to 25°C without changing the kinetics of the process. To retain thermolabile components, it is crucial to use lower drying temperatures, which can be achieved through PEF pre-treatment (12). PEF processing of apple before FD has been shown to reduce drying time and minimize changes in water activity during storage, likely due to increased sugar crystallinity. PEF-treated apples exhibit similar hygroscopic properties to untreated samples, which is important for storage and handling. However, they demonstrate better reconstitution, as evidenced by higher water absorption without a corresponding increase in soluble solids loss (56).

Osmotic dehydration-assisted freeze-drying in fruits

Osmotic dehydration (OD) is a technique used for the preservation of fruits by immersing them in a hypertonic solution, leading to water loss and solute gain within the fruit tissues. This process relies on the principle of osmosis, where water migrates from the fruit (a region of lower solute concentration) to the surrounding osmotic solution (a region of higher solute concentration) (57). The semi-permeable nature of the fruit's cell membranes allows this selective diffusion, enabling water to exit while some solutes may enter the fruit. This results in the reduction of water activity in the fruit, which is crucial for extending its shelf life by inhibiting microbial growth and slowing down enzymatic reactions that lead to spoilage (58).

The technique is valued for preserving the nutritional and sensory qualities of fruits, as it operates at ambient temperatures, thus avoiding the heat damage associated with other drying methods (59, 60). Moreover, this technique is energy-efficient and can be combined with other processes, such as air drying or FD, to achieve the desired moisture content while maintaining high product quality. The effectiveness of osmotic dehydration is influenced by factors such as the type of osmotic agent, temperature, immersion time and the geometry of the fruit pieces. Through these variables, the process can be optimized to enhance mass transfer rates, improve texture and preserve the natural flavours and colours of the fruit, making it a preferred method for producing high-quality dried fruit products (61, 62).

US-assisted OD as a pre-treatment technique before conducting FD in strawberries in another study that used fructose as an osmotic agent, which was combined with a firming agent such as calcium lactate and calcium chloride. It was discovered that the pre-treatment increased the freeze-dried samples' ability to rehydrate and improved the texture of the rehydrated strawberries. In addition, as compared to the untreated fruits, the freeze-dried sample's colour and structure were more intact. Significantly, the OD time was shortened as a result of using ultrasound (63).

On the other hand, dehydration of kiwi fruit using a combination of OD and FD methods. They optimized the OD process by using a sucrose solution at three different concentrations (40°B, 55°B, 70°B), three temperatures (40°C, 45°C, 50°C) and three time durations (2, 3 and 4 hr). The optimal conditions were found to be 40°B, 50°C and 3 hr, resulting in 60.75% water loss and 9.86% solute gain. After OD, the samples were freeze-dried using a Silver Coated Steel Heater (SCSH), which reduced the drying time to 2.5 hours, achieving a final moisture content of less than 5%. This method proved to be more energy-efficient compared to conventional FD techniques (64).

The study on raspberries explored the effects of sugar infusion pre-treatments combined with air- and freeze-drying on the physical and mechanical properties of the fruit. Different pre-treatments involved dry and wet sugar infusions, with additives like citric acid and sodium bisulfide. The study found that pre-treated raspberries had lower glass transition temperatures (Tg) and exhibited different mechanical properties compared to control samples. Freeze-dried raspberries were firmer and less deformable than air-dried ones. Additionally, freeze-dried samples were more hygroscopic. Pre-treated raspberries showed higher sugar content and a slight increase in water loss compared to control samples. The study concluded that these pre-treatments can effectively modify dried raspberries' texture and moisture properties, making them suitable for various food applications (65).

Limitations

Combined freeze-drying, also known as lyophilization, is a sophisticated preservation method that removes moisture from a product by freezing it and then applying a vacuum to sublimate the ice. Despite its effectiveness in preserving the structural integrity, flavour and nutritional value of products, combined freeze-drying has several limitations. One major drawback is its high cost due to the energy-intensive and time-consuming nature of the process, requiring specialized equipment and careful control of temperature and pressure conditions. This makes it less accessible for smaller-scale operations or developing countries (66). Additionally, freeze-drying can sometimes alter the texture of certain products, resulting in a brittle or porous structure that may not be desirable for all applications. Another limitation is the potential degradation of sensitive compounds during the freezing and sublimation stages, particularly if the process parameters are not optimized for the specific product. Moreover, the high sensitivity of freeze-dried products to moisture necessitates careful packaging and storage, as even minimal exposure to humidity can lead to rapid rehydration and spoilage. Overall, while combined freeze-drying offers superior preservation for many products, its cost, technical complexity and impact on certain materials present notable challenges.

Future thrusts

Challenges in hybrid freeze-drying technologies for fruits are poised to revolutionize the industry by addressing current limitations and enhancing efficiency. Key areas of focus include optimizing energy consumption and reducing drying times through advanced hybrid systems that combine freeze-drying with other drying techniques, such as microwave or vacuum-assisted drying. These hybrid approaches aim to retain the nutritional and sensory qualities of fruits while significantly lowering production costs. Another promising direction is the development of intelligent control systems that monitor and adjust the drying process in real-time, ensuring consistent product quality. Additionally, research is likely to explore the scalability of these technologies, enabling their application in large-scale industrial settings while maintaining environmental sustainability. The integration of these advancements could lead to the next generation of freeze-dried fruits, characterized by superior quality, extended shelf life and greater accessibility in global markets.

Conclusion

In conclusion, this review highlights the advancements and comparative studies of combination freeze-drying techniques, emphasizing the evolution of technology and the maintenance of product quality. Freeze-drying stands out among various drying techniques for its ability to preserve the "close to fresh" appearance and the integrity of heat-sensitive components. However, despite its widespread use in food, pharmaceuticals and other industries, concerns about the process and product costs persist. In recent years, researchers have introduced several pre-treatment methods and developed hybrid freeze-drying systems. These innovations offer significant benefits, including reduced drying times, lower process costs and improved product quality. The ongoing challenge is to scale these lab-tested methods to an industrial level.

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Authors' contributions

The author's contributions to the manuscript are as follows: VKS was involved in the conceptualization of the review, providing critical insights and finalizing the manuscript for submission. RV conducted the literature search, drafted the initial manuscript and created tables and figures. MI contributed by writing and summarizing sections on specific subtopics, while KGG assisted in writing and revising sections of the manuscript. BA performed the final revision and approved the manuscript. SM helped in establishing a framework for the literature review and RP verified data and references to ensure accuracy.

Compliance with ethical standards

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During the preparation of this work, we the authors used Sci space to make the table. After using this tool/service, we reviewed and edited the content as needed and took full responsibility for the content of the publication.

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