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REVIEW ARTICLE

Energy Consumption and Efficiency Optimization in Freeze Drying of Fruits and Vegetables: A Review

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Abstract

Fruits and vegetables are essential components of global food systems due to their nutritional and economic value; however, their high perishability contributes to substantial postharvest losses worldwide. Freeze drying is regarded as one of the most effective preservation methods, capable of maintaining structural integrity, nutritional content, and sensory attributes. Nonetheless, the process is energy-intensive and economically challenging at industrial scales. This review provides a comprehensive analysis of freeze drying as applied to fruits and vegetables, focusing on operational parameters—including freezing rate, chamber pressure, shelf temperature, and sample thickness—that significantly influence both product quality and energy consumption. Furthermore, this study highlights recent advances in hybrid and assisted freeze drying techniques, such as ultrasound, pulsed electric fields, and microwave integration, which demonstrate improvements in drying efficiency and bioactive compound retention. Industrial applications and techno-economic evaluations are also discussed to underscore the feasibility of adopting optimized freeze drying strategies. By synthesizing recent findings, this review aims to support the development of more sustainable and energy-efficient freeze drying systems, ensuring high-quality preservation of perishable agricultural commodities.

Keywords: freeze drying, energy efficiency, fruits and vegetables, process optimization, cryoprotectants

Introduction

Fresh agricultural products, particularly fruits and vegetables, play a crucial role in ensuring food security and nutrition, while also contributing to global trade and economic growth [1]. The global annual market value of fruits and vegetables at the farm level is estimated to reach approximately USD 1 trillion [2]. However, despite their high potential, fruits and vegetables are highly perishable commodities and remain vulnerable to significant postharvest losses (Figure 1) [3]. Globally, these products experience the highest rate of postharvest losses, ranging from 28% to 55% of total annual production, resulting in economic losses of up to USD 750 billion per year [4].

Postharvest losses in fruits and vegetables include quantitative losses such as mass reduction due to physiological, mechanical, or biological damage and qualitative losses, including diminished freshness, color, nutritional value, and visual appeal, all of which reduce marketability and economic value [5]. Pathogenic infections, such as those caused by *Botrytis cinerea*, are among the leading contributors to spoilage, with estimated global losses reaching up to USD 100 million annually [6]. These losses are exacerbated by limited storage facilities, inadequate handling, and poor postharvest infrastructure, particularly in developing countries, where a substantial proportion of harvested crops ends up as waste if not properly managed [7]. Without immediate intervention, global food losses are projected to double by 2050 and may account for up to 10% of global greenhouse gas emissions [3]. Valorization of agrobiomass such as rice straw into clean bioethanol energy has been identified as a sustainable alternative to utilize agricultural waste and support food diversification strategies in areas such as Central Java [8].

To mitigate these losses and maintain the nutritional quality of fruits and vegetables, effective preservation technologies are required, such as freeze drying. This method removes moisture through sublimation under low pressure, bypassing the liquid phase entirely [9]. Freeze-dried products retain desirable qualities such as vibrant color, high porosity, minimal shrinkage, and low water activity when compared to conventional drying techniques like convective or microwave drying [10]. Moreover, freeze drying effectively preserves bioactive compounds, shape, and overall appearance of the product [11]. With superior rehydration capacity and minimal thermal degradation, freeze drying produces outputs that closely resemble fresh products, making it one of the most effective methods for preserving the quality of fruits and vegetables [12]. Through additional pre-treatment such as fermentation with *Rhizopus oligosporus* and fortification using soy flour has been shown to significantly increase crude protein content and decrease bound tannin content for example in sorghum flour, thereby improving the functional quality and stability of the material during further drying processes such as freeze drying [13].

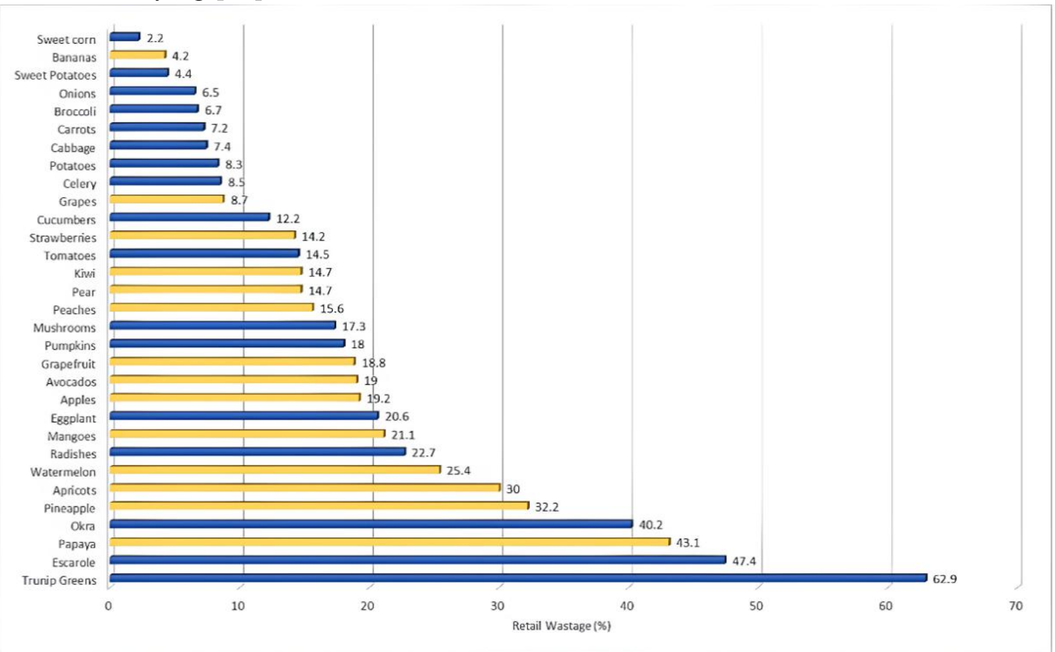

Figure 1. Percentage of loss and shelf-life stability of vegetables (green) and fruits (yellow) at the retail distribution level [5].

The efficiency of the freeze drying process is greatly influenced by various operational parameters that determine the quality of the final product as well as its energy consumption. The process consists of three main stages, namely freezing, primary drying (sublimation) and secondary drying (desorption), each of which requires precise control of temperature, pressure and duration to achieve optimal results [14]. Variables such as freezing rate, chamber pressure, rack temperature, and sample thickness greatly affect the drying rate as well as the final characteristics of the product [15]. Therefore, optimization of these parameters is crucial to ensure effective water removal without excess energy consumption, while preserving heat-sensitive compounds. Small changes in parameters such as freezing rate and pressure can lead to significant variations in the structural and nutritional quality of the final product [16]. In addition, the use of cryoprotectants plays an important role in maintaining material stability during the drying process by preventing aggregation and degradation of active compounds [17].

However, freeze drying also has significant disadvantages, especially in terms of energy requirements. Furthermore, renewable energy management is gaining importance in the agri-food sector. The use of livestock waste for energy generation via Combined Heat and Power (CHP) systems can achieve energy efficiency levels of up to 80%, offering a reference model for optimizing energy use in food processing applications [18]. Compared to conventional drying methods, this process requires large amounts of energy to maintain low temperatures and vacuum pressure for a long time. This leads to high operational costs and is a major challenge in the widespread application of freeze drying in large-scale industries [12]. High energy consumption not only impacts on production costs, but also on environmental sustainability aspects, especially when used in the processing of large quantities of food products.

Based on this background, this review aims to assess the energy efficiency of the freeze drying process and identify key variables that affect its performance. By understanding and optimizing these factors, it is expected that freeze drying technology can become more energy efficient and feasible to be widely applied, especially in the preservation of high-value agricultural products such as perishable fruits and vegetables.

Materials and Methods

Literature Selection

To compile this review, a systematic literature search was conducted focusing on studies related to freeze drying of fruits and vegetables, particularly those discussing energy efficiency and product quality. Inclusion criteria were as follows: (1) peer-reviewed journal articles published between 2010 and 2025, (2) studies that explicitly investigated freeze drying methods, whether conventional or combined with supporting technologies such as ultrasound, microwave, or PEF, and (3) articles presenting data or analysis on energy consumption, drying time, or product quality parameters (e.g., nutritional content, color, rehydration).

In addition, selected industrial websites and company reports were incorporated to complement academic insights with practical, large scale applications. These sources were included if they provided credible, technical descriptions of industrial scale freeze drying processes and technological focuses relevant to the objectives of this review.

Exclusion criteria included: (1) studies focusing solely on other drying methods without direct comparison to freeze drying, (2) studies lacking technical or quantitative data, and (3) non-scholarly publications such as company reports or opinion pieces.

Selected Materials

Fruits and vegetables are highly perishable and heat-sensitive food products, making freeze drying a preferred method for preserving their nutritional value and sensory quality, including color, flavor, and texture [19]. In this review, a range of fruit and vegetable commodities were examined based on their frequent use in freeze drying studies, particularly those focusing on energy consumption and process efficiency[20].

The most reviewed fruits include strawberries, mangoes, apples, blueberries, kiwis, starfruit, maoberries, pineapples, and red dragon fruit. Each of these fruits possesses distinct physical and chemical characteristics, such as initial moisture content, sugar concentration, and tissue structure, that directly impact energy requirements and final product quality during drying [21]. For instance, strawberries and maoberries have been widely studied for their ability to retain vitamin C and antioxidant activity [20]. Kiwis and apples were evaluated using Atmospheric Freeze Drying (AFD) to assess drying speed and vitamin retention [22]. Starfruit was used as a starter culture in sourdough fermentation, with an emphasis on preserving microbial viability post-drying [23].

Among vegetables, the most frequently studied commodities include carrots, spinach, bell peppers, beetroot, fermented napa cabbage, and sweet potatoes. Carrots were pretreated with ultrasound to enhance the retention of β-carotene and antioxidant compounds [24]. Spinach was compared between freeze drying and spray drying in terms of encapsulation efficiency and storage stability [25]. Bell peppers, beetroot, and napa cabbage were processed using advanced methods such as Pulsed Electric Field (PEF) and Microwave Freeze Drying (MFD) to improve structural integrity and reduce drying time [26]. Sweet potatoes were studied under Slot Jet Reattachment (SJR) drying and a combination of SJR with ultrasonic drying to improve energy and time efficiency while maintaining nutritional and textural quality [27].

The diverse selection of commodities in this review reflects a broad range of physical and chemical properties found in high-value fresh agricultural products. These materials serve as representative models for understanding how commodity-specific characteristics influence the performance and optimization of freeze drying processes [28].

Freeze Drying Process Overview

The fundamental principle of the freeze drying method is the removal of water content from the material through sublimation, which is the transition of water from a solid state (ice) directly into a gaseous state without passing through the liquid phase [29]. **Table 1** also indicates that freeze drying is the most effective preservation method for maintaining superior sensory quality, higher nutritional value, and better rehydration properties. In general, the freeze drying process consists of three main stages:

Table 1. Effect of Chiiling, Freezing, and Cold Storage

Method	Effect During The Process	Reference
Chilling	Water evaporation	[30]
	Chilling injury and cold contraction	[31]
	Changes of components such loss vitamin C in fruits and vegetables	[32]
	Undesirable changes of color, flavor, or taste	[33]
Freezing	Change of volume	[34]
	Redistribution of water	[35]
	Mechanical damage	[36]

Method	Effect During The Process	Reference
Cold Storage	Non-aqueous phase components being concentrated	[35]
	Recrystallization	[37]
	Freezer burn	[35]
	Oxidation and degradation of lipid	[38]
	Changes in pH, color, flavor, and nutritional components	[35]

a. Freezing Process

This process causes all components within the material, particularly water, to crystallize into ice, thereby helping to stabilize the position of components in the sample and preventing foaming during the vacuum stage [39]. Freezing is typically carried out at low temperatures, ranging from −20 °C to −80 °C. Rapid freezing results in the formation of small ice crystals, whereas slow freezing leads to larger crystals [40]. Larger ice crystals tend to create larger pores in the tissue structure of fruits or vegetables, which facilitates water vapor migration during drying but also poses a risk of damaging the tissue structure [41]. In contrast, smaller crystals may slow down sublimation and prolong the drying time, but they better preserve the structural integrity of the tissue.

b. Primary Drying Process

Once freezing is complete, the sample enters the primary drying phase, during which the majority of the formed ice (approximately 70–90%) is directly sublimated into water vapor under low-pressure (vacuum) conditions [42]. This sublimation occurs when the chamber pressure is below the triple point of water, allowing the phase transition from solid (ice) to gas without passing through the liquid phase [39]. Heat is transferred by conduction from the heating shelves (trays) within the freeze dryer to the ice interface forming on the material's frozen surface [43]. The ice layer at the surface sublimates first, followed gradually by deeper layers [40]. This stage is critical, as it determines the total freeze drying time and affects the final physical appearance of the product [44]. If not properly controlled, structural collapse may occur, reducing the product's porosity and rehydration capacity.

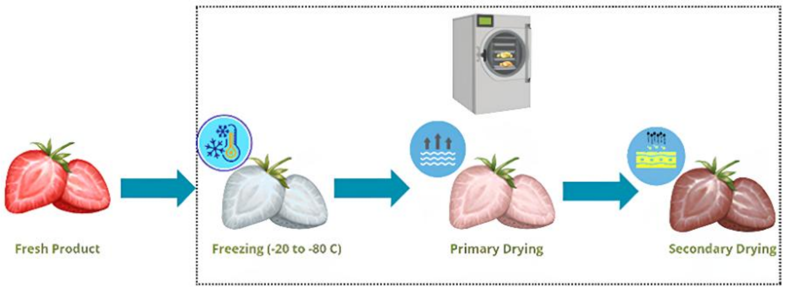

Figure 2. The main process of freeze drying

c. Secondary Drying Process

The secondary drying phase aims to remove the remaining bound water that cannot be eliminated through sublimation [39]. This water may exist in an amorphous (glassy) state or be adsorbed onto the surface of the material [45]. This phase proceeds more slowly and is also referred to as the desorption process, during which water evaporates through the microscopic pores of the product toward the surface and is then released as vapor [15].

Residual moisture content is typically reduced to below 5%, and can even be lowered to less than 1% when extended shelf life is required [42]. In fruit and vegetable products, a low final moisture content is essential to prevent nutrient degradation, microbial growth, and sensory changes during storage.

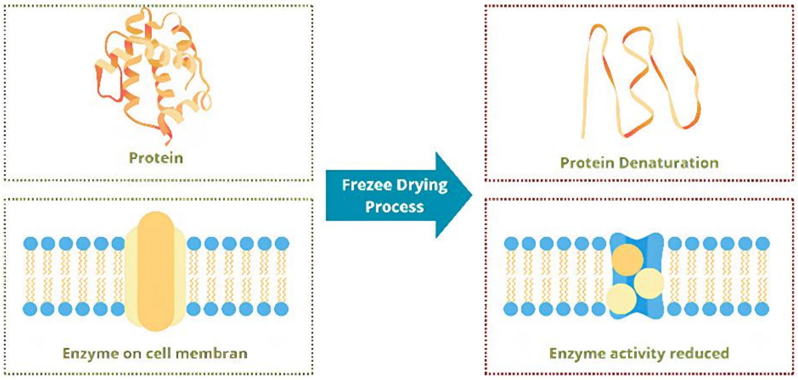

Figure 3. Structural and biochemical during freeze drying [39]

During the freeze-drying process, the formation of ice crystals can damage the membrane structure and cell walls of fruit and vegetable tissues [39]. This disruption leads to increased permeability, cellular fluid leakage, and a reduction in the tissue's ability to maintain its shape and texture. Freeze drying may also reduce the activity of enzymes such as polyphenol oxidase (PPO) and peroxidase (POD), which in turn affects the product's color, texture, and freshness [46]. In addition to enzymes, structural proteins can undergo denaturation due to low-temperature and dehydration stress, especially when sublimation occurs either too slowly or too rapidly [47].

Nevertheless, freeze drying is generally effective in retaining bioactive compounds such as vitamin C, anthocyanins, flavonoids, and total phenolics, although slight degradation may still occur. This preservation is notably better than that achieved by other drying methods like oven drying or hot air drying [48]. Several studies have shown that fruits such as maoberry, strawberry, and mulberry dried using this method exhibit more stable antioxidant activity and natural coloration [49]. However, the effectiveness of freeze drying is highly dependent on the type of commodity and the process parameters. In certain cases such as with walnut kernels alternative methods like gradient hot drying have demonstrated better bioactive stability [50].

Results and Discussion

Freeze drying is widely acknowledged as a superior method for dehydrating fruits and vegetables due to its ability to retain structural integrity, nutrients, and volatile compounds better than conventional thermal drying methods [51]. Despite its advantages, traditional freeze drying is often associated with high energy consumption and extended drying times [12]. Various methodological approaches from recent studies have demonstrated the ability to reduce drying duration and energy consumption, while simultaneously maintaining or even enhacing the final product quality.

Table 2. Summary of Freeze Drying Methods, Conditions, and Quality Outcomes in Fruit and Vegetables

Commodity	Drying Method	Operating Conditions	Energy/ Drying	Quality Parameters	Results	Ref.

			Time	Evaluated		
Banana	Vacuum Freeze Drying (VFD)	480 minutes, low pressure (standard VFD)	3,967 kWh	Color, pH, rehydration, °Brix, shrinkage, microstructure	Uniform structure, minimal shrinkage, high rehydration ratio	[52]
Carrot	Ultrasound-pretreated Freeze Drying	-72°C, 0.0001 mbar, 24 h; ultrasound, 5 min	Not stated	β-carotene, phenolics, flavonoids, antioxidants, structure	High bioactive retention, porous structure	[53]
Blueberry	Freeze Drying	−20°C to 20°C, 20 Pa	Modeled; sublimation time predicted	Drying kinetics, structure, surface pressure	Model 2 effectively predicted sublimation; skin = main resistance	[54]
Apple & Kiwi	Atmospheric Freeze Drying (AFD)	−20°C → 10°C (stepwise), atmospheric pressure	AFD faster than LTD	Vitamin C, shrinkage, drying time	AFD improved drying speed and retained more vitamin C	[55]
Kiwi, Bell pepper, Beetroot	PEF + Freeze Drying	PEF 1.0 kV/cm, 0.2–20.8 kJ/kg;	Freeze drying time reduced 50% (bell pepper)	Volume retention, color (ΔE), rehydration	Structure preserved; ΔE > 3 unless stored in darkness	[56]
Starfruit (Starter Culture for Sourdough)	Freeze Drying + Cryoprotectant (Sucrose, Glucose, Fructose	Freezing: −24°C for 24 hours. Drying: 72 hours (3 days).	Not stated	Cell viability (LAB & Yeast), Shelf life, Protein, Phenol, Sensory	Sucrose 10% = best: 7.75 log CFU (LAB) & shelf life 56 days. Gluten ↓ 68%, Antioxidants ↑. Sensory almost equivalent to fresh starter	[57]
Red Dragon Fruit	Infrared Drying + Pretreat	Mid-IR drying: 60°C, 900 W, distance	Drying time: 220–380 min	ΔE, RR, shrinkage, hardness, TPC,	- Highest def TSFT: 4.17×10^{-8} m^2/s - Better color,	[58]

	ments (TSFT, MWFT, CP, US, EC, MWB, IRB)	15 cm, tray rotation 40 rpm TSFT: −20°C (12 h), thawing 50°C (5 min)	TSFT ↓ 42%, MWFT ↓ 36.8%, MWB ↓ 31.6%	betalain, ascorbic acid, antioxidant	RR, shrinkage, and texture in TSFT & MWFT.	
Maoberry	Freeze Drying vs Hot Air Drying (50–100 °C)	FD: −55 °C, 0.1 mbar, 24 h Hot Air: 50–100 °C, airflow 0.5 m/s, 2.35–8 h	FD: 24 h @ −55 °C, 0.1 mbar Hot Air: 2.35–8 h	TPC, TFC, TAC, ascorbic acid, HMF, microbes	FD maintains: • Ascorbic acid: 86.6 mg/100g DW (vs 10 mg @100°C) • Highest TPC, TFC, TAC HMF < 100 ppm in all methods	[59]
Cabbage (Fermented napa cabbage)	Hot Air Drying (HAD), Vacuum Freeze Drying (FD), Microwave Freeze Drying (MFD).	HAD: 55 °C, air 1 m/s. FD: −25 °C pre-frozen, 1 Pa vacuum. MFD: −25 °C pre-frozen, vacuum 200 Pa, microwave 300 W.	MFD: 2 hours, lowest energy HAD: 4 hours FD: 18 hours, highest energy	Rehydration, microstructure, pH, amino acids, aroma, probiotics, vitamin C, polyphenols, antioxidants, sensory.	MFD produces products with the best rehydration and quality, retaining probiotics, nutrients, aroma, and the best energy and time efficiency compared to HAD and FD.	[60]
Sweet potato	Slot Jet Reattachment (SJR) drying, Ultrasonic contact drying combined with	SJR and SJR + US: temperature 40, 50, and 60 °C, air velocity 3 m/s, 20 kHz ultrasound (pulsed) for SJR + US	Longest FD (48 hours) and highest energy SJR + US and SJR	Rehydration, shrinkage, color, texture, total starch, dietary fiber, β-carotene, vitamin C, total phenolics, flavonoids,	SJR + US at 50 °C gave the best quality close to FD, with high rehydration, maintained nutrition, good color and texture, and lower energy	[61]

	SJR (SJR+US), Hot Air Drying (HAD), Freeze Drying (FD)	HAD: temperature 40, 50, and 60 °C, air 3 m/s FD: freezing −40 °C, vacuum 0.08 mBar, duration 48 hours	faster than HAD and FD (time not specified, but more efficient) SJR + US reduces time and energy compared to HAD and FD	antioxidant activity, glass transition temperature.	and time consumption than HAD and FD.	
Spinach extract	Spray Drying (SD) and Freeze Drying (FD).	SD: air inlet 170 ± 5 °C, outlet 85 ± 5 °C, air flow 600 l/h, feeding rate 5 ml/min. FD: temperature −86 °C, pressure 5 mbar, duration 42 hours.	Not stated	Water content, water activity, powder yield, encapsulation efficiency, particle morphology, storage stability.	FD produces higher yield and encapsulation efficiency, while SD provides better storage stability.	[62]

Following the comprehensive comparison in **Table 2**, it is important to further analyze the effectiveness and efficiency of various freeze drying approaches applied to fruits and vegetables. Various approaches both conventional and those incorporating pretreatments or auxiliary technologies, have been developed to addres the primary limitations of freeze drying.

Effectiveness of Freeze Drying Methods

Conventional Vacuum Freeze Drying (VFD) continues to be a gold standard for preserving the quality of fruits and vegetables, yielding products with excellent structural integrity, minimal shrinkage, and high rehydration capacity [63]. However, combining freeze drying with pretreatments has proven even more effective. Ultrasound-assisted freeze drying on carrots significantly increased retention of β-carotene and antioxidants while creating a porous microstructure ideal for rehydration [53]. PEF-assisted freeze drying halved the drying time for bell pepper and preserved the structure and rehydration characteristics, although notable color degradation ($\Delta E > 3$) occured without light protection [56]. In a similar hybrid approach, starfruit starter cultures preserved via freeze drying with sucrose as cryoprotectant maintained viable microbial cells for 56 days while enhancing antioxidant content and sensory acceptance in sourdough applications [57].

In addition, Atmospheric Freeze Drying (AFD) provided a more energy-efficient alternative while preserving vitamin C better than Low Temperature Drying (LTD), as demonstrated in apple and kiwi [55]. Futhermore, in spinach extract encapsulation, Freeze Drying achieved higher powder yield and encapsulation efficiency compared to spray drying, confirming its effectiveness for microstructure-sensitive application [62]. These examples suggest that hybrid freeze drying methods (e.g., with ultrasound, PEF, or cryoprotectants) are generally more effective than conventional freeze drying alone, especially when the goal is to retain nutritional and functional quality while achieving structural preservation [64]. This is likely because pretreatments modify the microstructure of the material such as breaking down cell walls, increasing porosity, or softening tissues, thus enhancing the rate and uniformity of sublimation [65].

As a result, sensitive bioactive compounds like vitamin C, phenolics, and flavonoids are better protected from degradation, and physical attributes such as colour, rehydration ratio, and texture can be maintained more consistently [66]. Moreover, by reducing internal resistance to mass transfer, these methods enable faster drying without compromising the integrity of the final product, which is especially important for high-value, heat-sensitive commodities [67].

Energy Efficiency and Drying Time

Energy consumption and drying time remain significant limitations for traditional freeze drying. For example, Vacuum Freeze Drying (VFD) of bananas required 3.967 kWh over 8 hours [52], while the Freeze Drying process for strawberries lasted up to 60 hours to achieve <10% final moisture content [11]. Similarly, Freeze Drying for fermented napa cabbage took 18 hours and consumed the most energy among the compared methods [60].

In contrast, Microwave Freeze Drying (MFD) dramatically reduced energy usage and time. MFD of napa cabbage dried the product in just 2 hours while retaining superior quality and rehydration capacity compared to both Freeze Drying and Hot Air Drying [60].This show that direct volumetric heating by microwaves enhances internal heat transfer and accelerates water sublimation, thereby cutting down drying time significantly.

Likewise, Slot Jet Reattachment (SJR) combine with ultrasound (SJR+US) on sweet potato achieved product quality nearly equivalent to Freeze Drying (FD), while significantly reducing energy and time inputs [61]. In pineapple, Microwave-Assisted Freeze Drying (MAFD) cut energy use by 34.5% compared to conventional Freeze Drying (FD), delivering comparable texture and moisture retention [68]. Methods such as microwave irridation are also relevant as efficient drying approaches, as this technique can increase thermodynamic efficiency by up to 1.3 times compared to conventional heating [69]. For dragon fruit, the application of thermo-ultrasound and microwave freeze-thaw pretreatments reduced infrared drying time by up to 42%, while preserving antioxidant content and improving physical attributes such as color, shrinkage, and texture [58]. Similarly, freeze drying of maoberry was found to be much more effective than hot air drying in retaining total phenolics, flavonoids, and ascorbic acid [59].

According to the reviewed studies, hybrid and assisted freeze drying technologies such as MFD, MAFD, SJR+US, and pretreatment-enhanced FD offer significant improvements in energy efficiency and time optimization. This is largely because these techniques either improve heat and mass transfer during drying (e.g., microwave volumetric heating, ultrasound cavitation) or prepare the material microstructure in advance (e.g., PEF, freeze-thaw), reducing the resistance to water migration [67]. Consequently, drying becomes faster, energy input is minimized, and overall production becomes more sustainable and cost effective without compromising the nutritional, structural, or sensory quality of the product [70]. This makes hybrid freeze drying systems especially promising for scaling up in commercial food processing industries where both performance and quality are equally critical [71].

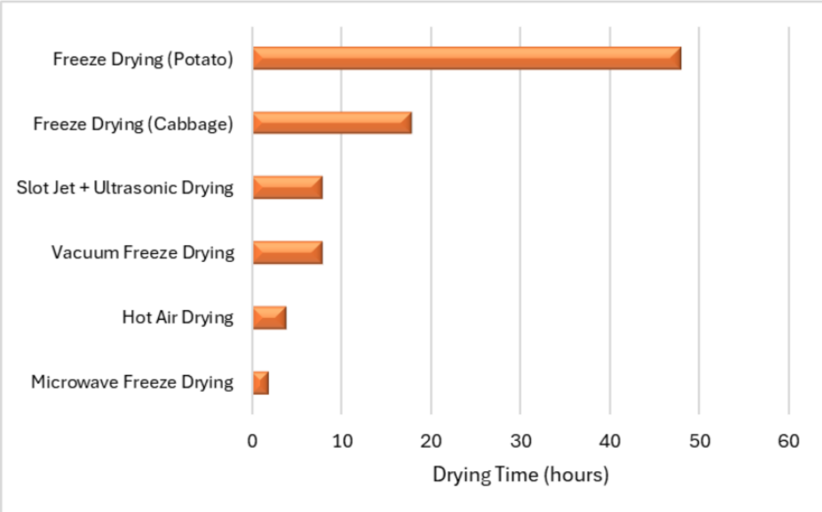

Figure 4. Comparison of drying time consumption between drying methods

Optimized Operating Conditions

In addition to the factors mentioned above, temperature and pressure play an important role in the final product yield to improve energy efficiency, maintain quality, and extend the shelf life of food commodities [72]. For example, vacuum freeze drying (VFD) of bananas is carried out at low pressure for 480 minutes, resulting in a uniform structure and high rehydration power [52]. Similarly, freeze-dried carrots after ultrasound treatment at -72°C and 0.0001 mbar pressure for 24 hours showed high bioactive retention and a porous structure [53]. The use of freeze drying (FD) in vegetables, for example the use of extreme freezing temperatures, such as -86°C in freeze drying spinach extracts, resulted in high encapsulation efficiency and yield, despite the 42-hour time required [62]. In contrast, the spray drying method on spinach, which uses an air inlet temperature of 170°C, offers better storage stability, suggesting a trade-off between nutrient quality and process efficiency.

At moderate temperatures, atmospheric freeze drying (AFD) of apples and kiwis was carried out gradually from -20°C to 10°C at atmospheric pressure, which accelerated drying time and improved vitamin C retention compared to the low-temperature drying (LTD) method [55]. Pulsed electric field (PEF) treatment of kiwi, beetroot and peppers, combined with freeze drying, reduced drying time by 50% and preserved volume and color, although color changes were more pronounced unless stored in the dark [56]. The innovation of PEF shows that pretreatment can accelerate drying kinetics and improve porosity and rehydration ability without damaging the internal structure.

In comparison, the hot air drying (HAD) method at high temperature 50-100°C showed better time efficiency, but caused significant degradation of heat-sensitive nutrients, such as ascorbic acid in maoberry which decreased drastically from 86.6 mg/100g (FD) to only 10 mg/100g at 100°C [59]. Microwave freeze drying (MFD) is emerging as an attractive alternative, such as in fermented cabbage, as it is able to shorten the drying time to 2 hours (compared to 18 hours for FD), while maintaining optimal rehydration, aroma, vitamins and probiotics, thanks to volumetric heating and low pressure (200 Pa) [60]. The combination of infrared drying with pretreatment such as Thermoultrasound-Mediated Freeze-Thaw (TSFT) and Microwave-Mediated Freeze-Thaw (MWFT) on red dragon fruit at 60°C shortened drying time by 42% compared to the control, while maintaining color, texture, and bioactive content ([58].

Other approaches such as Slot Jet Reattachment (SJR) drying and the combination of SJR + ultrasonic drying at 40-60°C resulted in quality close to freeze drying, especially in sweet potato, but with lower energy and time consumption [61]. This combination demonstrates process efficiency without sacrificing essential nutrients such as β-carotene and vitamin C. In contrast, methods such as spray drying, which operate at high inlet temperatures (170°C), while efficient in terms of time and storage stability, tend to reduce bioactive qualities if not optimized.

Overall, freeze drying is still the best method for maintaining nutritional quality and microstructure, but it is expensive and time-consuming. The pre-freezing temperature at -20°C and -80°C affects the survival rate and stability of the product during freeze drying, thus affecting the final freeze dried product [73]. Alternative methods that combine moderate temperature, lighter pressure, and pretreatment (such as ultrasound, PEF, microwave, and SJR) show great potential for process efficiency without significantly compromising product quality. The selection of the best method also largely depends on the characteristics of the food commodity, the ultimate goal on product nutrition and efficiency, and the availability of technology.

Freeze Drying Product Quality Compared to Conventional Methods

Freeze drying method with sublimation process under vacuum pressure and ultra-low temperature is able to maintain the physical, chemical and nutritional quality of the product better than conventional drying methods such as hot air drying. The earliest advantage in freeze drying is that it is able to overcome structural damage and minimize the loss of flavor and aroma compounds in foods, as well as improve rehydration ability and minimize decomposition reactions while maintaining the structural integrity of foods, but this method may cause loss of flavor and aroma in foods [74]. Optimal freeze drying operational conditions, for example, at low pressure and high temperature within certain limits can minimize nutrient degradation due to the faster drying process [75].

Freeze dried food products have brighter colors, better preserved aroma, and unique textures such as crisp and light, in contrast to conventional drying products which tend to be hard and lose aroma [11]. Freeze dried products have high microbiological stability that increases nutritional value and antioxidants as well as a longer shelf life without the need for additional preservatives [76]. In maintaining the microstructure, freeze drying is more effective than conventional drying methods because annealing increases the size of ice crystals, resulting in a larger pore structure and a more stable dry tissue [77]. The physical changes of the freeze drying method are still smaller than those of conventional drying, which can cause more severe structural damage. However, freeze drying methods require longer time and high energy consumption compared to conventional drying, making production more expensive and less economical for bulk products [78]. Development of hybrid methods such as heat-assisted freeze drying or infrared radiation can be done to reduce time and cost without compromising product quality.

Economic Analysis of Freeze Drying Implementation

In the application of freeze drying technology in the food industry, beyond quality and energy efficiency considerations, economic aspect are also critical in determining feasibility. According to Kourkoutas et al. [79], the largest investment component in a freeze drying system lies in the drying equipment, accounting for 57% of total investment. However, increasing production scale significantly reduces the production cost per kilogram from €15.4/kg to €2.9/kg, demonstrating that larger-scale operations can accelerate the payback period.

In addition, recent innovations have enabled better energy efficiency. Keller et al [80] showed that optimizing the cooling system in freeze drying, particularly by replacing synthetic refrigerants and incorporating heat pump systems, can yield substantial energy savings during the primary drying phase. This efficiency becomes crucial given that freeze drying is known to be energy-intensive. Thus, an efficient system design not only reduces power consumption but also shortens the return-on-investment period, especially for large-scale facilities.

Hence, although freeze drying requires high initial investment, both in term of energy and equipment, applying energy efficiency strategies and optimizing production scale can make this technology economically viable and competitive in the long term.

Application

Various approaches have been developed to address the high energy consumption associated with freeze drying, one of which is the integration of supportive technologies such as microwave-assisted freeze drying (MAFD) and infrared-assisted freeze drying (IRAFD) ([40]. Studies have shown that the use of MAFD for pineapples can save up to 34.5% in energy consumption and reduce drying time by 33.3% compared to conventional freeze drying [68]. Meanwhile, IRAFD has also shown promising results. In the drying of moonflowers and banana snacks, it achieved energy savings of 15–36% and drying time reductions of 8–30%, without compromising final product quality [81].

In addition to physical approaches like microwave and infrared integration, chemical strategies can also be adapted in fruit and vegetable processing. This includes the addition of protective compounds (such as sugars, amino acids, and metal ions) that help preserve cellular structures during freezing and drying [39]. Pretreatment techniques such as blanching, ultrasound (US), and pulsed electric field (PEF) have been shown to reduce freeze-drying time and preserve the bioactive compounds in fruits and vegetables [46]. These methods also contribute to maintaining key quality attributes including color, flavor, and rehydration capacity leading to improved final product quality [82]. For instance, PEF and its combination with ultrasound were found to be more effective than blanching alone in preserving the physical and nutritional quality of red bell peppers [83].

Table 3. Application Freeze Drying In Industry

Company	Product	Technology Method	Focused
Lyovit [84]	Fruit, Vegatable, Herbs & Spices	Freeze drying + Vacuum-Steam Sterilization	Maintaining the original texture and nutritional value by reducing moisture content to below 3%, allowing the product to meet microbiological standards.
Natierra [85]	Fruit and Vegatable	Freeze drying with a focus on organic & fair trade products	Maintains natural shape and nutrition suitable for healthy retail & snacks
Berrifine [86]	Fruit and Vegatable	Freeze drying, air drying, spray drying and vacuum drying	The process naturally retains and preserves as many vitamins and minerals as possible. Also given to the protection of color and texture and, most importantly, the taste of fruit.
Europan Freezedry [87]	Fruit, Vegatable & Pulses, Meat, Seafood, Dairy, & Eggs	Freeze Drying Conventional	Maintaining shape, taste, and especially vitamin content
Chaucer Foods [88]	Fruit, Vegatable, Cheese, Powder, and Freeze-dried melts	Freeze Drying Conventional	Producing products with nutritional content up to 97% equivalent to fresh fruit, bright colors, authentic flavors, and long shelf life that supports logistics efficiency and food waste reduction.

Table 3 shows that various global companies have implemented freeze-drying technology on an industrial scale with diverse approaches and focuses. This technology is effective in preserving product quality but faces a major challenge in high energy consumption due to the need for low pressure and freezing temperatures over extended periods. This challenge becomes more significant at the industrial level due to long processing times and the need for specialized equipment, resulting in increased operational costs [40]. To address this, companies apply efficiency strategies such as batch size optimization, use of renewable energy, and improved vacuum chamber design. In addition, hybrid approaches like microwave-assisted freeze drying have been developed to accelerate the process and reduce energy consumption without compromising product quality.

Conclusions

Freeze drying remains a premier preservation method for fruits and vegetables due to its unparalleled ability to maintain nutritional quality, structural integrity, and sensory attributes. However, its application at industrial scale is hindered by high energy consumption and prolonged processing times. Through this review, we highlighted how process innovations—such as ultrasound-assisted, microwave-assisted, and pulsed electric field (PEF)-integrated freeze drying—can significantly enhance energy efficiency while preserving or even improving product quality. These findings underscore the importance of tailoring freeze-drying strategies to the specific physicochemical properties of different commodities. For instance, highly porous fruits may benefit more from ultrasound-assisted drying, while fibrous vegetables may require different pretreatments to optimize water removal and nutrient retention. From a broader perspective, the optimization of freeze-drying processes has far-reaching implications for global food systems. By reducing postharvest losses and extending shelf life without compromising quality, energy-optimized freeze drying can support food security, minimize waste, and contribute to sustainable food processing practices—particularly in developing regions lacking cold chain infrastructure. Moreover, as hybrid drying technologies continue to evolve, future research should focus on the scalability, economic feasibility, and environmental impact of these approaches. Integrating renewable energy sources and adopting smart control systems could further enhance sustainability. Ultimately, translating laboratory-scale insights into commercially viable solutions will be critical for the widespread adoption of efficient freeze drying in the global fruit and vegetable industry.

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