Emerging Food-Drying Technologies for Nutritional Quality Preservation and Energy-Efficient Processing: A Review

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Abstract- Food drying is an essential preservation operation in the food industry and contributes to the development of shelf-stable ingredients and consumer products. Industrial food-drying technologies, including pretreatments, processing methods, equipment, and quality-control systems, have advanced considerably in recent years. Novel approaches, including microwave-assisted drying, ultrasound-assisted drying, high-electric-field drying, heat-pump drying, and refractance-window drying, have demonstrated the potential to improve process efficiency, reduce energy consumption, and preserve both product quality and nutritional value. Despite encouraging laboratory-scale findings, the industrial adoption of many of these technologies remains limited because of high capital costs, scale-up challenges, inconsistent performance data, and limited awareness among commercial operators. This review critically examines the principles, advantages, limitations, energy requirements, quality effects, and industrial applications of emerging food-drying technologies. Particular attention is given to hybrid systems, intelligent process control, renewable-energy integration, and the factors that influence commercial implementation. Current evidence indicates that hybrid and sensor-assisted drying systems may offer the most practical route toward more sustainable and quality-oriented food processing. However, further techno-economic assessment, pilot-scale validation, and standardized reporting of energy and quality outcomes are required.

Index Terms- food drying, food safety, hybrid drying, infrared drying, vacuum drying

I. INTRODUCTION

Since ancient times, food drying and dehydration have been used to preserve foods, extend shelf life, reduce microbial and enzymatic deterioration, and facilitate storage and transportation. However, conventional drying approaches frequently require substantial energy inputs and may cause deterioration in nutritional, physicochemical, and sensory quality. Consequently, modern food-preservation research has increasingly focused on developing drying technologies that improve energy and process efficiency while maintaining, or potentially enhancing, product quality [1]. From a human nutrition perspective, preserving the nutritional quality of dried foods is equally important because appropriate drying technologies can minimize losses of vitamins, minerals, dietary fiber, and health-promoting phytochemicals during processing.

Emerging drying technologies include infrared drying, vacuum-microwave drying, radio-frequency drying, refractance-window drying, ultrasound-assisted drying, and light-assisted dehydration. Compared with conventional hot-air drying, several of these methods can shorten processing time, improve energy utilization, and enhance the retention of flavour, colour, texture, and heat-sensitive nutrients. UV-A-assisted dehydration has also been investigated as a low-temperature or non-thermal supportive treatment that may reduce microbial loads and therefore offer potential benefits for heat-sensitive food products [2]. In addition, researchers have examined microwave-assisted, ultrasound-assisted, high-electric-field, and refractance-window systems because of their capacity to enhance moisture transport and preserve product quality [1,6,7].

The integration of optical sensing and artificial intelligence has further advanced the development of precision food-drying systems. Real-time monitoring of moisture content, temperature, colour, and surface characteristics can support dynamic adjustment of process conditions and improve operational consistency. RGB imaging, near-infrared spectroscopy, and near-infrared hyperspectral imaging have been applied to evaluate drying progression and product quality without destructive sampling [3]. Moreover, intelligent systems incorporating the Internet of Things, machine-learning algorithms, and digital-twin frameworks may enable predictive modelling, fault detection, adaptive control, and improved batch-to-batch consistency [16,33].

These developments have considerable potential to improve food preservation, reduce energy demand, and enhance product quality. Nevertheless, the commercial relevance of a novel technology depends not only on its drying rate but also on capital cost, operating cost, scalability, maintenance requirements, product compatibility, energy source, and regulatory acceptance. Therefore, a comprehensive evaluation should consider both technical performance and industrial feasibility.

The principal purposes of food drying are to: (i) extend the availability and shelf life of perishable foods; (ii) convert fresh materials into stable dried products while maintaining acceptable nutritional, structural, and sensory quality; (iii) reduce product mass and volume to facilitate packaging, transportation, and storage; and (iv) improve the sustainability of processing operations, particularly because many drying processes consume substantial amounts of energy at relatively low thermal efficiencies [4]. Accordingly, emerging technologies should provide measurable advantages in energy efficiency, product quality, process duration, cost, and environmental impact [28,34].

More than 50 dryer configurations have been developed, although not all are technically or economically suitable for food applications [5]. Microwave drying, ultrasound-assisted drying, superheated-steam drying, heat-pump drying, and refractance-window drying have shown promising results in laboratory and pilot-scale studies [6,7,12]. However, commercial implementation remains uneven because of high investment costs, complex process control, limited scale-up evidence, and uncertainty concerning actual energy savings under industrial operating conditions. This gap between laboratory performance and industrial adoption represents a central challenge in the field [16,28].

Accordingly, this review evaluates recent developments in conventional, novel, and hybrid food-drying technologies, with particular emphasis on their mechanisms, energy performance, quality effects, limitations, and practical industrial implications. It also examines intelligent control, renewable-energy integration, commercialization barriers, and priority areas for future research. In addition, the review highlights the importance of selecting drying technologies that preserve nutritional quality while improving process efficiency, thereby supporting the production of healthier and more sustainable food products. For clarity, the technologies reviewed in this article are organized into three principal categories according to their dominant energy-transfer mechanism and process configuration: electromagnetic-radiation techniques, combined or hybrid drying methods, and low-temperature techniques (Figure 1).

Figure 1. Hierarchical classification of the principal novel food-drying technologies

II. ELECTROMAGNETIC-RADIATION-BASED DRYING TECHNIQUES

Most conventional large-batch drying systems transfer heat primarily by convection using hot air generated by electrical heaters, heat exchangers, or combustion gases. In contrast, electromagnetic drying methods deliver energy directly to the product surface or interior, thereby increasing the heating rate and potentially accelerating moisture removal [7]. In these systems, electrical energy is converted into electromagnetic radiation and subsequently into thermal energy within or on the surface of the food material [36,53].

A. Microwave Drying

Microwave drying is a volumetric dielectric-heating process in which electromagnetic energy interacts with polar molecules and ions within the food matrix. Their rapid oscillation and movement generate thermal energy, which promotes water evaporation and moisture transport. Microwave radiation occupies wavelengths from approximately 1 mm to 1 m, whereas frequencies of 915 MHz and 2450 MHz are most commonly used in food-processing applications.

Because microwave energy can generate heat throughout the product volume, microwave drying can achieve substantially shorter drying times than conventional hot-air drying. It may also provide favourable energy efficiency and quality retention when process conditions are carefully controlled. However, microwave-field non-uniformity, variations in dielectric properties, limited penetration depth, and rapid local temperature increases can result in hot spots, edge overheating, textural damage, scorching, or non-uniform final moisture content [8,51]. Recent studies on microwave drying of catfish fillets reported higher effective moisture diffusivity than hot-air drying, indicating more rapid moisture removal [26,38]. Nevertheless, the reported values of 4.84 W/g and 18.74 kJ/mol represent different physical quantities and should not be presented as a direct comparison of energy requirements. The original studies should be rechecked, and energy-performance data should be reported using equivalent units and clearly defined system boundaries.

B. Infrared Drying

Infrared drying involves exposing food materials to electromagnetic radiation within a wavelength range of approximately 0.75–1000 µm. Infrared energy is absorbed at or near the product surface and converted into heat through molecular vibration. Unlike conventional convective heating, infrared radiation does not require the surrounding air to serve as the primary heat-transfer medium. The relatively simple equipment, rapid heating response, and potential for energy-efficient operation make infrared drying particularly suitable for integration with conventional drying methods [10,35]. Far-infrared radiation is frequently investigated for moisture removal and the preservation of bioactive compounds, whereas near-infrared radiation may promote rapid surface heating and colour or flavour development, including Maillard reactions, in carbohydrate-rich foods [17,49]. Infrared blanching used as a pretreatment has been reported to reduce drying time by as much as 50% and lower energy consumption by approximately 17% in selected products [21,49]. However, such performance values are product- and equipment-specific and should not be generalized without reporting radiation intensity, emitter distance, sample thickness, temperature, and airflow conditions.

C. Radio-Frequency Drying

Radio-frequency heating is used in both communication technologies and industrial food processing; however, its food-processing application is based on dielectric heating rather than wireless transmission. During radio-frequency heating, food is positioned between electrodes and exposed to an alternating electric field, commonly within the industrial, scientific, and medical frequency bands. Polar molecules and dissolved ions respond to the rapidly alternating field, generating heat through molecular rotation and ionic conduction.

Because water is strongly responsive to dielectric fields, radio-frequency energy can produce relatively rapid volumetric heating and promote moisture evaporation. Compared with microwaves, radio-frequency energy may offer greater penetration depth, making it potentially suitable for thicker or bulk food materials. Nevertheless, electrode configuration, product geometry, dielectric-property variation, and non-uniform electric-field distribution can produce uneven heating [9,29]. Recent multi-stage radio-frequency drying strategies have demonstrated promising results for agricultural products, particularly when radio-frequency heating is combined with hot-air drying or tempering periods [19,29]. Further industrial studies are required to establish product-specific process windows, safety controls, and reliable energy-performance benchmarks.

D. Refractance-Window Drying

Refractance-window drying is a film-based drying technique that combines conduction, convection, and radiation heat transfer. Liquid or semi-liquid food is spread as a thin layer over a transparent polymer film that floats on, or remains in close contact with, circulating hot water. Thermal energy is transferred through the film to the food layer, facilitating rapid moisture removal. The process generally operates at atmospheric pressure, and the circulating-water temperature is often substantially higher than 30°C, commonly within approximately 70–95°C depending on the system and product. Therefore, the claim that the process operates at approximately 30°C should be removed unless it is supported by the cited source. Although the heating medium may be hot, evaporative cooling can maintain the product at a lower temperature during much of the drying period, which contributes to the preservation of heat-sensitive components.

Refractance-window drying has been applied to fruit and vegetable purees, herbal extracts, and other pumpable products [11]. Some studies have reported a processing-time reduction of approximately 61% compared with conventional concentration or drying systems, with reported energy efficiencies between 28% and 38% [11]. The technique may preserve phenolics, antioxidant activity, vitamin C, colour, and aroma at levels comparable to, or in some cases better than, conventional drying methods [11,37]. Its principal limitations include restriction to thin layers of liquid, puree, or semi-liquid materials; potential degradation or replacement requirements for polymer films; limited capacity for large particles; and the need for careful control of film thickness and water temperature. The major characteristics of the principal novel drying technologies, including their operating mechanisms, applications, advantages, limitations, and key findings reported in the literature, are summarized in Table 1.

Table 1. Comparative analysis of novel food drying technologies based on drying time, energy consumption, and product quality retention

Drying Technology	Mechanism	Advantages	Key Limitations	Food Applications	Key Findings	References
Microwave Drying (MD)	Volumetric dielectric heating (915/2450 MHz)	Rapid drying; high energy efficiency; volumetric heating	Non-uniform heating; overheating; product damage	Fruits, vegetables, herbs, fish	Higher moisture diffusivity than hot-air drying	[26,38]
Infrared Drying (ID)	Surface heating by infrared radiation (0.8–1000 μm)	Fast drying; high energy efficiency; simple equipment	High equipment cost; limited penetration	Fruits, vegetables, mushrooms	Up to 50% shorter drying time; higher efficiency	[6,21,49]
Radio-Frequency Drying (RF)	Dielectric heating by alternating electric field	Uniform volumetric heating; suitable for bulk products	High capital cost; complex design	Nuts, grains, tea leaves	Lower energy use than hot-air drying	[9,29]
Refractance Window Drying (RW)	Heat transfer through heated transparent film	Low-temperature drying; good nutrient retention	Limited to liquid/semi-liquid foods	Fruit pulps, herbal extracts	61% shorter processing time; high bioactive retention	[11,37]
Vacuum-Microwave Drying (VMD)	Microwave heating under reduced pressure	Rapid drying; excellent quality retention	Expensive equipment; uneven microwave heating	Berries, carrots, herbs, fish	Superior colour, texture, and rehydration	[20,30,32,52]
Freeze Drying (FD)	Ice sublimation under vacuum	Best quality retention; long shelf life	Expensive; slow; energy intensive	Fruits, coffee, pharmaceuticals	Excellent preservation of nutrients and structure	[4,21]
Ultrasound-Assisted Drying	Acoustic cavitation enhances mass transfer	Lower drying temperature; improved quality	Specialized equipment required	Fruits, vegetables, pretreatments	Improved moisture transfer and carotenoid retention	[14,40]
Intermittent Drying (IMD)	Alternating heating and tempering cycles	Energy saving; improved product quality	Complex process control	Fruits, vegetables, grains	Reduced browning and energy consumption	[9,20,38]

III. COMBINED AND HYBRID DRYING METHODS

Individual drying technologies frequently exhibit limitations related to heating uniformity, energy demand, processing time, or product quality. Hybrid drying systems seek to overcome these limitations by combining complementary heat- and mass-transfer mechanisms. Several hybrid methods have been investigated for food applications, although their industrial feasibility varies according to product characteristics, equipment cost, and control requirements [45]. Hybrid systems represent an important direction in next-generation food processing because they may reduce processing time while improving product quality and energy utilization [16,45].

A. Microwave-Assisted Convective Drying

Hot-air drying is widely used for fruits, vegetables, and aromatic herbs because of its operational simplicity and industrial familiarity. However, conventional convective drying may require prolonged processing and can produce surface hardening or case formation at elevated temperatures. Microwave-assisted convective drying can reduce these disadvantages by combining surface moisture removal through hot-air convection with volumetric heating by microwave energy. During the early stages of drying, hot air removes free moisture from the product surface, while microwave energy promotes internal heating and facilitates the movement of moisture from the interior toward the surface [6,42]. This complementary mechanism may shorten drying time and improve energy efficiency. However, careful control of microwave power, air temperature, air velocity, product thickness, and treatment duration is required to prevent local overheating. Optimization studies on probiotic-enriched apple snacks reported that microwave-convective drying at 90 W and 50°C produced favourable colour and texture characteristics [15]. These conditions should be presented as product-specific experimental findings rather than as universally optimal operating parameters.

B. Vacuum-Microwave Drying

Vacuum-microwave drying combines microwave heating with reduced-pressure operation. Lowering the chamber pressure reduces the boiling point of water, allowing rapid moisture removal at lower product temperatures. The method can therefore satisfy several important drying objectives, including rapid processing, relatively high energy-transfer rates, reduced thermal damage, and favourable retention of nutritional and sensory quality. The vacuum accelerates moisture removal and can increase the internal pressure gradient, whereas microwave energy supplies volumetric heat. Together, these effects promote rapid low-temperature drying. Vacuum-microwave drying has been applied successfully to fruits, vegetables, herbs, berries, and animal-derived products [52]. However, the non-uniform distribution of microwave energy remains a major limitation and may result in overheating at sample edges and corners [12,51]. Product rotation, mode stirrers, pulsed microwave application, power modulation, and appropriate load design can help reduce this problem.

For berries, vacuum-microwave drying has been reported to produce superior colour, texture, and rehydration characteristics compared with conventional drying, with quality approaching that of freeze-dried products but at lower processing time and potentially lower energy consumption [20,30]. An optimization study of tilapia fillets identified a sample thickness of 7 mm, microwave power of 330 W, and vacuum pressure of 0.06 MPa as favourable experimental conditions [22,32]. The pressure value should be clarified as absolute pressure or vacuum gauge pressure because these definitions are not interchangeable.

C. Convective Predrying Followed by Vacuum-Microwave Finishing

Convective predrying followed by vacuum-microwave finishing is a two-stage process designed to combine the relatively low cost of hot-air drying with the rapid final-moisture removal and quality advantages of vacuum-microwave drying. This strategy has been applied to sour cherries, jujube, orange peel, beetroot, blackcurrant, pumpkin, plums, and hemp materials [13,14]. Studies of two-stage drying have also reported improvements in energy use and quality for maize and other commodities [23,31]. Nevertheless, claims that the combined method is more efficient than either individual process should be supported with comparable energy data, identical final-moisture targets, and clearly defined system boundaries.

D. Fluidized-Bed Drying Assisted by Microwaves, Infrared Radiation

Microwave energy can be combined with fluidized-bed drying to enhance internal heating while maintaining strong external heat and mass transfer. Fluidization improves particle mixing and surface exposure, whereas microwave energy accelerates volumetric moisture removal. However, equipment design is complex, and microwave coupling may vary as product moisture content changes. Scale-up is challenging because stable fluidization, microwave-field uniformity, particle residence time, and airflow must be controlled simultaneously. High initial equipment costs may also limit commercial adoption. Far-infrared radiation may also be combined with fluidized-bed or convective systems. Infrared energy can provide rapid surface heating at different stages of drying and has been investigated for maintaining quality and controlling compounds such as allicin during garlic processing.

High-power ultrasound can enhance the drying of heat-sensitive foods by increasing mass transfer through acoustic cavitation, microstreaming, and structural deformation. Because ultrasound may allow lower temperatures or shorter processing periods, it can contribute to the preservation of colour, nutrients, and cellular structure [14,40]. Ultrasound-assisted osmotic dehydration has also been used as a pretreatment to improve water removal and preserve quality attributes during subsequent drying [15,40]. This suggest that ultrasound-assisted drying is inherently cost-effective should be moderated because economic performance depends on transducer efficiency, equipment cost, product throughput, and processing scale.

E. Intermittent Drying

Drying is among the most energy-intensive operations in food processing. Intermittent drying aims to reduce energy use and thermal damage by periodically varying or interrupting heat application. Temperature, humidity, airflow, pressure, radiation intensity, or microwave power may be altered over time, and active drying periods may be separated by tempering periods.

During tempering, internal moisture redistributes toward the product surface, potentially increasing the drying rate when heating resumes. Intermittent operation may therefore reduce continuous thermal exposure, limit internal stress, and help preserve nutrients and bioactive compounds [15,20]. The technique may also reduce browning, structural collapse, and undesirable chemical reactions. Intermittent drying was developed in response to common limitations of conventional drying, including long processing times, high energy consumption, and quality deterioration [20]. However, its effectiveness depends strongly on the duration and frequency of heating and tempering cycles. Poorly optimized intermittency may increase total elapsed processing time without producing meaningful energy savings.

IV. FREEZE-DRYING

Freeze-drying, or lyophilization, is a low-temperature dehydration process in which a product is frozen and the surrounding pressure is reduced so that ice can sublimate directly into water vapour. It is particularly effective for preserving heat-sensitive foods, pharmaceuticals, biological materials, and high-value ingredients. The process consists of three principal stages: freezing, primary drying, and secondary drying. During primary drying, frozen water is removed through sublimation. During secondary drying, a proportion of the remaining bound or adsorbed water is removed through desorption. Freeze-dried products commonly exhibit extended shelf life, high porosity, rapid rehydration, and good retention of original structure, flavour, colour, and bioactive compounds [17,21]. However, freeze-drying requires expensive vacuum and refrigeration equipment, long processing periods, and substantial energy inputs. Product collapse, incomplete drying, lipid oxidation, and loss of volatile compounds may also occur if freezing rate, shelf temperature, chamber pressure, or packaging conditions are inadequately controlled. Infrared-assisted freeze-drying has been investigated as a means of increasing heat transfer and producing crisp fruit snacks. Microwave-assisted freeze-drying may also accelerate sublimation by supplying volumetric energy, although it requires sophisticated equipment and precise control to avoid electrical discharge, uneven heating, or structural damage [17,21]. From an industrial perspective, freeze-drying is most appropriate for high-value products whose quality premiums justify the high processing cost.

V. PRESERVATION OF FRUITS, VEGETABLES, AND HERBS

A wide variety of dryers has been developed for fruits, vegetables, and herbs. Commonly applied methods include convective drying, spray drying, freeze-drying, osmotic dehydration, solar drying, heat-pump drying, and combinations of these approaches. Conventional methods remain widely used because of their operational simplicity and established industrial infrastructure. However, they can cause colour loss, shrinkage, surface hardening, aroma loss, oxidation, nutrient degradation, and high energy consumption. Extensive research has therefore focused on reducing these disadvantages and improving energy performance [39]. Novel technologies that may achieve greater industrial acceptance include heat-pump dryers, renewable-energy-assisted systems, hybrid dryers, and methods that allow more precise control of temperature, humidity, airflow, product moisture, and quality indicators [18,24,43,46]. Renewable-energy-based systems integrating solar, wind, biomass, or waste-heat recovery with intelligent control mechanisms may offer more sustainable alternatives to fossil-fuel-powered drying [24,33,44,46,47]. However, renewable systems must address fluctuations in energy availability, climatic dependence, storage requirements, process reliability, and food-safety control. Maintaining the nutritional quality of dried fruits, vegetables, and herbs is particularly important because these products contribute essential micronutrients, dietary fibre, and bioactive compounds to the human diet throughout the year. The selection of an appropriate drying technology should consider both product characteristics and processing objectives, as summarized in Figure 2.

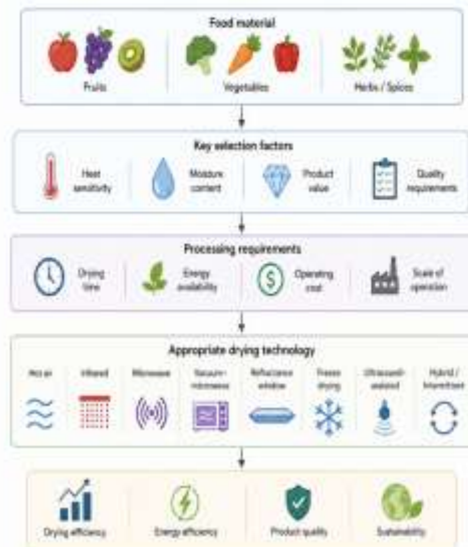

Figure 2. Conceptual framework illustrating the selection of food-drying technologies.

VI. ADVANTAGES AND LIMITATIONS OF NOVEL FOOD-DRYING TECHNOLOGIES

Novel technologies, including infrared drying, vacuum-microwave drying, freeze-drying, microwave-assisted freeze-drying, intermittent drying, ultrasound-assisted drying, and high-electric-field drying, have been developed to address limitations associated with conventional food drying.

Their potential advantages include shorter drying times, improved energy utilization, reduced processing temperatures, and better preservation of colour, flavour, texture, nutrients, and bioactive compounds. Improved retention of nutrients and bioactive compounds may also enhance the nutritional value of dried foods, particularly for products consumed as important sources of antioxidants, vitamins, and phytochemicals. Infrared drying, for example, can provide rapid and relatively uniform surface heating when emitter distance and radiation intensity are carefully controlled [35,36]. Vacuum-microwave drying combines low-pressure operation with volumetric heating and is therefore suitable for heat-sensitive fruits and vegetables [19,52].

Nevertheless, novel technologies also present important limitations. Infrared systems may involve high investment costs and are not equally effective for all materials [19,36]. Vacuum-microwave systems require complex vacuum and microwave equipment and may produce non-uniform heating [19,51]. Freeze-drying preserves product quality effectively but is costly, energy intensive, and time consuming [20,21]. Microwave-assisted freeze-drying can shorten processing time but requires specialized equipment and remains limited in industrial application.

Ultrasound-assisted drying is not yet widely adopted because transducer design, acoustic coupling, treatment uniformity, and process-control requirements remain challenging [21,40]. Intermittent drying requires accurate control of heating and tempering cycles. High-electric-field and electrohydrodynamic drying systems may offer low-temperature moisture removal, but scale-up, electrode safety, field uniformity, ozone generation, and throughput remain important concerns. High capital costs, equipment complexity, limited scale-up evidence, and uncertain economic returns remain major barriers to industrial adoption [16,20,28]. Therefore, laboratory demonstrations should be followed by pilot-scale trials, life-cycle analysis, techno-economic assessment, and direct comparison with established industrial systems. Freeze-drying is particularly suitable for delicate fruits, coffee, high-value ingredients, and other products for which flavour, aroma, porosity, and rehydration quality justify the processing cost [21,37]. Microwave assistance may accelerate freeze-drying and reduce processing time, although energy savings should be validated at the complete-system level. Ultrasound-assisted drying may increase mass transfer and improve textural and nutritional retention [40,41]. Film-based preservation technologies have also emerged as potential complementary approaches for meat products. However, film formation, edible coatings, and active packaging should not be classified directly as drying technologies unless water removal is their principal mechanism. A comparative summary of the reported advantages, limitations, and representative applications of conventional and emerging food-drying technologies is presented in Table 2.

Table 2. Advantages and disadvantages of conventional and novel drying methods for food preservation

Drying Method	Reported Advantages	Reported Limitations	Representative Applications	References
Sun Drying	Low cost; simple operation; no external energy requirement	Long drying time; contamination risk; weather dependence; poor quality control	Fruits, vegetables, cereals	[2]
Hot Air (Convective) Drying	Simple operation; low capital cost; widely adopted	Long drying time; shrinkage; colour and nutrient loss; case hardening	Fruits, vegetables, herbs, grains	[7]
Freeze Drying (FD)	Excellent retention of nutrients, colour, flavour, and structure; high rehydration capacity	High energy consumption; expensive equipment; long processing time	High-value fruits, coffee, pharmaceuticals	[4,7,12,21]
Infrared Drying (ID)	Rapid heating; short drying time; good colour retention; high energy efficiency	Limited penetration depth; distance-sensitive heating; high equipment cost	Fruits, vegetables, mushrooms	[7,10,35]
Microwave Drying (MD)	Rapid volumetric heating; reduced drying time; improved energy efficiency	Non-uniform heating; overheating; texture damage	Fruits, vegetables, herbs, fish	[8,10,51]
Vacuum-Microwave Drying (VMD)	Rapid low-temperature drying; excellent colour, texture, and nutritional retention	High capital cost; complex equipment; uneven microwave heating	Berries, carrots, herbs, fish	[20,30,52]
Refractance Window Drying (RW)	Rapid drying; good retention of bioactive compounds; suitable for heat-sensitive products	Limited to liquid and semi-liquid products; specialized equipment	Fruit and vegetable pulps, herbal extracts	[11,37]
Microwave-Assisted Freeze Drying	Faster than conventional freeze drying; improved energy efficiency	High equipment cost; limited industrial application	High-value fruits and specialty products	[17,21]
Ultrasound-Assisted Drying	Enhanced mass transfer; lower drying temperature; improved quality retention	Specialized equipment; limited commercial adoption	Fruits, vegetables, pretreatments	[14,40]
Solar Hybrid Drying	Renewable energy utilization; reduced operating cost; lower greenhouse gas emissions	Weather dependence; intermittent energy supply; higher installation cost	Fruits, vegetables, medicinal plants	[33,44,46]
Heat Pump Drying	High energy efficiency; low-temperature drying; improved product quality	High installation cost; complex system design	Fruits, vegetables, seafood	[10,43]

VII. FUTURE PERSPECTIVES

Future food-drying systems are expected to integrate intelligent sensing, artificial intelligence, renewable energy, and digital twin technologies into a unified processing platform (Figure 3). Machine-learning-enabled sensors may support dynamic adjustment of temperature, airflow, humidity, pressure, microwave power, and treatment duration, thereby reducing uneven heating, nutrient degradation, and unnecessary energy consumption [16,33].

Figure 3. Emerging technological trends in food drying

Moisture content, temperature, colour, shrinkage, texture, and chemical-quality indicators may increasingly be monitored in real time using optical, spectroscopic, acoustic, or dielectric sensors. These data can be incorporated into predictive models that estimate drying endpoints and maintain consistent product quality across batches and product types. Future studies should also incorporate standardized nutritional quality indicators, including vitamin retention, antioxidant capacity, mineral bioaccessibility, and protein quality, alongside conventional engineering performance metrics.

Digital twins may provide virtual representations of dryers, products, and process conditions. When combined with computational fluid dynamics, heat- and mass-transfer models, and real-time sensor data, digital twins may facilitate equipment design, fault prediction, optimization, and adaptive process control [24,45,46]. However, their industrial value will depend on model accuracy, sensor reliability, data interoperability, cybersecurity, and the ability to update models as raw-material properties change.

Integration of renewable energy, heat recovery, thermal storage, and waste-heat utilization may reduce the carbon footprint of food dehydration [24,45,46]. Solar-assisted heat pumps, biomass-supported systems, and hybrid renewable-energy dryers may be particularly relevant in regions with limited grid reliability or high solar availability.

Future research should move beyond reporting drying kinetics alone. Greater emphasis is required on specific energy consumption, exergy efficiency, water activity, nutrient retention, sensory acceptance, equipment cost, carbon emissions, throughput, cleaning requirements, and life-cycle performance.

Standardized reporting frameworks are also needed. Studies should clearly describe initial and final moisture contents, product load, sample geometry, air conditions, energy-metering boundaries, dryer efficiency definitions, and quality-analysis methods. Without such standardization, comparisons among technologies remain uncertain.

Scalable systems should be validated under continuous or semi-continuous industrial conditions rather than exclusively under small laboratory batch conditions. Collaboration among food scientists, process engineers, equipment manufacturers, economists, and industrial operators will be essential for translating experimental innovations into commercially viable technologies.

VIII. CONCLUSION

Growing consumer demand for nutritious, convenient, and shelf-stable foods has increased interest in advanced dehydration technologies. For fruits, vegetables, herbs, and other heat-sensitive products, drying methods must preserve nutritional, physicochemical, structural, and sensory characteristics while achieving microbial stability and acceptable energy performance.

Novel approaches such as microwave, infrared, radio-frequency, ultrasound-assisted, vacuum-microwave, refractance-window, heat-pump, and intermittent drying can provide important advantages over conventional hot-air drying. However, their effectiveness varies according to product composition, geometry, moisture content, equipment design, and operating conditions. Hybrid systems appear particularly promising because they combine complementary heat- and mass-transfer mechanisms. Convective predrying followed by vacuum-microwave finishing, microwave-assisted hot-air drying, infrared-assisted systems, and renewable-energy-supported heat-pump drying may reduce processing time and thermal damage while improving energy utilization.

Freeze-drying remains a benchmark technology for the preservation of structure, bioactive compounds, and rehydration quality. Nevertheless, its high cost and energy demand restrict its use primarily to high-value products. Pretreatments such as osmotic dehydration, pulsed electric fields, ultrasound, blanching, and edible coatings may improve process efficiency and product quality, but their effects must be evaluated for each food matrix. Overall, the future of food drying is likely to depend on the integration of hybrid technologies, renewable energy, real-time sensing, artificial intelligence, and digital-twin-based process control. The most important research priorities are industrial-scale validation, standardized energy reporting, economic feasibility, life-cycle assessment, food-safety evaluation, and the development of robust control systems. Ultimately, the successful development of emerging food-drying technologies should not only improve energy efficiency and industrial productivity but also maximize the preservation of nutritional quality, thereby supporting the production of healthier, safe, and sustainable food products for consumers.

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