



ISSN Print: 2618-060X
 ISSN Online: 2618-0618
 NAAS Rating (2026): 5.20
 IJRA 2026; SP-9(9): 598-607
www.agronomyjournals.com
 Received: 27-06-2026
 Accepted: 25-08-2026
 Published: 30-09-2026

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Novel drying and dehydration technologies for millet-based foods: Energy efficiency, quality retention and scale-up challenges

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i9Sg.6730>

ABSTRACT

This review critically evaluates conventional, emerging and hybrid drying technologies for millet-based foods, with emphasis on drying characteristics, energy efficiency, quality retention and challenges of industrial scale-up. We synthesised published literature on drying fundamentals; conventional and novel drying technologies; drying kinetics; nutritional and bioactive quality; energy and thermodynamic performance; storage stability; rehydration behaviour; and scale-up considerations. Technologies reviewed include microwave, infrared, vacuum, freeze, heat-pump, Refractance Window and hybrid drying systems. Emerging and hybrid technologies can enhance moisture removal, shorten drying time and improve process control compared with conventional approaches under suitable operating conditions, although performance is strongly influenced by millet type, product form and process parameters. Drying time alone is insufficient to judge technology suitability; specific energy consumption, energy and exergy efficiency, heating uniformity, structural change, nutritional and bioactive retention, colour, texture, rehydration, storage stability and equipment cost must be evaluated together. Hybrid systems allow drying rate, energy consumption and product quality to be balanced. Future development should focus on product-specific process optimisation and standardised kinetic, energy, thermodynamic, nutritional, sensory and economic evaluation. Pilot- and industrial-scale validation, energy recovery, renewable-energy integration and intelligent process control remain priorities for translating novel drying technologies into commercially viable, sustainable millet-processing systems.

Keywords: Millets, Drying technologies, Dehydration, Energy efficiency, Quality retention, Hybrid drying

1. Introduction

Millets are a group of small-seeded cereals that have gained considerable attention for their nutritional value, adaptability to diverse agro-climatic conditions and contribution to sustainable food systems. Important cultivated millets include pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), little millet (*Panicum sumatrense*), kodo millet (*Paspalum scrobiculatum*), barnyard millet (*Echinochloa* spp.) and proso millet (*Panicum miliaceum*). Millet grains are important sources of carbohydrates and proteins and also contain dietary fibre, minerals, vitamins and phytochemicals, including phenolic compounds and other bioactive constituents (Saleh *et al.*, 2013) [1]. These characteristics have driven growing interest in millets as ingredients for conventional, functional and value-added foods. Pearl millet and other millets are also recognised for tolerance to drought and other environmental stresses, making them relevant to climate-resilient agriculture and nutritional security (Satyavathi *et al.*, 2021) [2]. Millet utilisation has expanded well beyond traditional foods: millet grains are converted into flour and used in bakery products, porridges, extruded foods and snacks, while germination, fermentation and other operations yield value-added products that can influence nutritional, physicochemical and functional characteristics and therefore product quality, convenience and acceptability (Saleh *et al.*, 2013; Anju *et al.*, 2021) [1, 3]. Improved postharvest processing technologies are increasingly recognised for their potential to expand millet utilisation and value addition (Dinesh *et al.*, 2025) [4].

Drying is an essential unit operation in the preservation of millet-based foods and ingredients. Its principal purpose is to reduce moisture content to a level that limits microbial growth and slows undesirable chemical and biochemical reactions; the accompanying reduction in weight and volume also facilitates handling, packaging, storage and transport. Drying is particularly important for millet products subjected to cooking, soaking or germination, since these operations raise moisture content substantially — for example in the production of instant foxtail millet and finger millet porridge powder, where drying strongly influenced physicochemical, nutritional, structural and rehydration properties (Kabeer *et al.*, 2023; Wang *et al.*, 2022) [5, 6]. Drying is, however, an energy-intensive operation whose requirement depends on initial moisture content, drying temperature, air velocity, bed depth, product properties and dryer configuration. Studies on Kodo millet have highlighted the importance of energy utilisation, exergy loss and exergy efficiency during fluidized-

bed drying (Yogendrasasidhar *et al.*, 2018) [7], and similar exergy-based evaluation of continuous multistage fluidized-bed drying of barnyard millet has demonstrated the relevance of dryer configuration and operating conditions to both energy performance and continuous industrial processing (Yogendrasasidhar *et al.*, 2019) [8]. Energy consumption must therefore be considered alongside drying time and product quality when evaluating any drying technology.

Conventional hot-air drying remains widely used because of its simple operation and established equipment, but prolonged exposure to heated air can cause shrinkage, structural modification, colour change, reduced hydration capacity and altered starch characteristics. In gelatinized foxtail millet, hot-air and microwave drying produced structural and starch changes associated with poorer rehydration, whereas freeze drying better preserved structure and hydration behaviour (Wang *et al.*, 2017) [9]. (Wang *et al.*) [6] similarly reported that microwave-vacuum, microwave-hot-air, hot-air and traditional roasting treatments produced different drying times, moisture diffusivities, colour, phenolic content, pigment retention and sensory properties in instant foxtail millet. Microwave drying of sprouted little millet altered antinutritional factors, dietary fibre and mineral bioavailability at different power levels (Jena *et al.*, 2025) [10], and drying technique likewise influenced the physicochemical and nutritional characteristics of finger millet porridge powder, with differences among spray, tray and freeze-drying treatments (Kabeer *et al.*, 2023) [5]. Together these findings show that achieving a target moisture content is not sufficient; the drying method and conditions must also be matched to the required final quality, since advanced drying technologies can simultaneously affect several quality attributes.

Novel and hybrid drying technologies have therefore attracted growing interest as alternatives or complements to conventional drying. Microwave, microwave-assisted hot-air, infrared, vacuum, freeze, fluidized-bed, heat-pump and hybrid systems differ in their mechanisms of heat and mass transfer, and consequently in drying kinetics, energy requirement and quality impact (Wang *et al.*, 2022; Yogendrasasidhar *et al.*, 2018; Yogendrasasidhar *et al.*, 2019; Wang *et al.*, 2017) [6, 7, 8, 9]. However, drying-time reduction alone cannot establish the suitability of a novel technology. Specific energy consumption, energy and exergy efficiency, nutritional and bioactive retention, colour, texture, rehydration, storage stability, cost, throughput and scale-up feasibility are equally important, because laboratory-scale performance may not represent industrial performance once product loading, air-flow distribution, equipment dimensions and heat-transfer conditions change (Yogendrasasidhar *et al.*, 2019) [8]. This review therefore critically evaluates novel drying and dehydration technologies for millet-based foods, focusing on drying kinetics, energy efficiency, and nutritional, physicochemical, functional and sensory quality, with particular attention to process optimisation, techno-economic feasibility and industrial scale-up.

2. Millets as a raw material for dehydrated and dried foods

Millets are small-seeded cereal grains increasingly used as nutritious raw materials for conventional, functional and value-added food products. They are rich in carbohydrates and also supply protein, dietary fibre, minerals, vitamins and bioactive phenolic compounds. Composition varies with species, cultivar, growing conditions and processing history, and these differences influence moisture behaviour, drying characteristics, energy requirement and final product quality (Saleh *et al.*, 2013; Satyavathi *et al.*, 2021) [1, 2]. Understanding raw-material characteristics is therefore essential for selecting suitable dehydration technologies and optimising drying conditions.

2.1 Major millets

Pearl millet (*Pennisetum glaucum*), cultivated widely in semi-arid and drought-prone regions, contains carbohydrates, protein, dietary fibre, minerals, vitamins, phenolic compounds and an appreciable proportion of unsaturated fat; it is used in flour, porridge, bakery products,

snacks and other value-added foods (Saleh *et al.*, 2013; Satyavathi *et al.*, 2021) [1, 2]. Finger millet (*Eleusine coracana*), widely consumed in India and parts of Africa, is notable for high calcium content alongside carbohydrates, protein, fibre and iron, and is commonly processed into flour, porridge, malted products, bakery items and instant foods (Hithamani *et al.*, 2014) [11]. Foxtail millet (*Setaria italica*) contains carbohydrates, protein, fibre, minerals and phenolics and is used in traditional and modern instant foods, porridges, snacks and flour products; drying strongly influences drying time, moisture diffusivity, colour, phenolic retention and rehydration in instant foxtail millet products (Wang *et al.*, 2022) [6]. Little millet (*Panicum sumatrense*), an important small millet in traditional systems, provides carbohydrates, protein, fibre and bioactive compounds whose nutritional and functional properties are modified by germination, drying and milling; microwave drying of sprouted little millet has been studied for its effect on antinutritional factors, dietary fibre and flour rheology (Jena *et al.*, 2025) [10]. Kodo millet (*Paspalum scrobiculatum*), a hardy millet adapted to dry conditions, is used for flour and traditional as well as value-added products; its drying characteristics have been evaluated through fluidized-bed drying kinetics and energy-exergy analysis (Yogendrasasidhar *et al.*, 2018) [7]. Barnyard millet (*Echinochloa* spp.), recognised for its fibre and nutrient content, is used in porridges and cereal-based dishes; continuous multistage fluidized-bed drying has been investigated from energetic and exergetic perspectives (Yogendrasasidhar *et al.*, 2019) [8]. Proso millet (*Panicum miliaceum*) is nutrient-rich and used in porridges, bakery products, snacks and flour-based foods (Saleh *et al.*, 2013; Satyavathi *et al.*, 2021) [1, 2]. These compositional and structural differences among species influence water binding, moisture migration, drying rate and final product quality.

2.2 Nutritional characteristics

Carbohydrates, chiefly starch together with dietary fibre and other non-starch polysaccharides, are the major component of millet grains; starch structure and composition influence gelatinization, pasting behaviour, digestibility and processing-related structural change (Saleh *et al.*, 2013; Satyavathi *et al.*, 2021) [1, 2]. Millet proteins — albumins, globulins, prolamins and glutelins — vary among species and cultivars and influence water absorption, texture and functional behaviour; thermal processing and drying can alter protein structure and its interaction with other components (Saleh *et al.*, 2013; Satyavathi *et al.*, 2021) [1, 2]. Dietary fibre, present in both soluble and insoluble forms (cellulose, hemicellulose, lignin and other polysaccharides), affects water absorption, swelling, texture and moisture movement during drying (Saleh *et al.*, 2013; Satyavathi *et al.*, 2021) [1, 2]. Millets supply important minerals — calcium, iron, phosphorus, magnesium, potassium and zinc — with finger millet particularly notable for calcium; mineral bioavailability can, however, be reduced by antinutritional compounds such as phytate and tannins (Hithamani *et al.*, 2014) [11]. B-group vitamins (thiamine, riboflavin, niacin) vary with species, cultivar and processing, and because some are heat-sensitive, drying temperature and duration must be controlled to limit losses (Saleh *et al.*, 2013; Satyavathi *et al.*, 2021) [1, 2]. Phenolic acids, flavonoids and tannins occur in free and bound forms and contribute to antioxidant activity and sensory characteristics; their stability and extractability are altered by drying and other processing (Saleh *et al.*, 2013; Hithamani *et al.*, 2014) [1, 11]. Antioxidant potential, associated mainly with phenolic compounds and other phytochemicals, differs among species and can be affected by drying temperature, time and oxygen exposure, making antioxidant retention an important criterion for evaluating novel drying technologies.

2.3 Moisture characteristics

Moisture is the principal factor governing storage stability, drying behaviour, microbial safety and energy demand in millet grains and millet-based foods. Initial moisture content — the water present before drying, expressed on a wet or dry basis — largely determines drying time and energy requirement; processed millet foods (germinated,

cooked or hydrated products) generally start with considerably higher moisture than raw grain and therefore require carefully controlled drying to achieve stability without undesirable quality change. Equilibrium moisture content is the level at which a material reaches balance with the surrounding air at a given temperature and relative humidity, with no net moisture exchange; sorption studies on millet grains confirm that this value depends on temperature and relative humidity (Anju *et al.*, 2021) [3] and is useful for defining the minimum moisture achievable under given ambient conditions. Moisture migration — movement of water from the interior toward the surface, driven by concentration and water-activity gradients through liquid diffusion, vapour diffusion and capillary flow — becomes increasingly important as drying proceeds and is a key control on the later stages of drying and overall drying time. Moisture sorption, the capacity of a material to gain or lose moisture from the surrounding atmosphere, is commonly represented through sorption isotherms relating equilibrium moisture content to water activity or relative humidity at a given temperature; sorption studies on millet seeds show that equilibrium moisture depends on temperature and humidity (Menkov *et al.*, 2000) [12], information that is useful for setting target final moisture content, designing moisture-barrier packaging and predicting the storage stability of dried millet products.

3. Fundamentals of drying and mass transfer

Drying is fundamentally a simultaneous heat and mass transfer process. Heat supplied to the wet material causes moisture to evaporate, and the resulting water vapour is transferred to the surrounding drying air by conduction, convection or radiation depending on dryer type; in most hot-air systems convection dominates (Jimoh *et al.*, 2023) [13]. The heat supplied is used partly to raise product temperature and mainly to provide the latent heat of vaporisation. Moisture within the grain moves by liquid diffusion, capillary flow and vapour movement and must migrate from the interior to the surface before removal by the drying air, so internal structure, porosity, particle size, initial moisture content and composition govern the rate of moisture removal, with the driving force arising from the difference in moisture concentration or vapour pressure between product and air (Jimoh *et al.*, 2023) [13].

Moisture content, expressed on a wet or dry basis, decreases continuously during drying; comparison across conditions commonly uses the moisture ratio,

$$MR = (M - M_e) / (M_0 - M_e)$$

where M is the moisture content at time t , M_0 the initial moisture content and M_e the equilibrium moisture content. When M_e is small relative to M_0 and M , this simplifies to $MR \approx \frac{M}{M_0}$. The resulting drying curve (moisture ratio against time) underpins mathematical modelling and comparison of drying technologies (Wang *et al.*, 2022) [6] and is particularly important for millet, where it also governs subsequent milling and processing behaviour (do Nascimento *et al.*, 2015; Goneli *et al.*, 2010) [14, 15].

Drying rate — the moisture removed per unit time — is governed by drying-air temperature, velocity, relative humidity, initial moisture content, product loading and grain structure. Many foods pass through an initial warming period, a constant-rate period and a falling-rate period, but millet grains show predominantly falling-rate behaviour, reflecting the growing importance of internal moisture movement as drying proceeds (do Nascimento *et al.*, 2015; Srinivasakannan *et al.*, 2009) [14, 16]. The falling-rate period intensifies at lower moisture content once easily removable surface moisture is depleted and water must travel from the grain interior to the surface. Increasing temperature or air velocity generally accelerates moisture removal within an appropriate operating range, but excessively severe conditions can damage colour, texture, nutrients and bioactive compounds; studies on instant foxtail millet (Wang *et al.*, 2022) [6] and fluidized-bed drying of Kodo millet (Yogendrasasidhar *et al.*, 2018) [7] both confirm

the strong influence of operating conditions on drying performance and energy use, and semi-empirical models such as the Page model have been used to describe fluidized-bed millet drying (Srinivasakannan *et al.*, 2009) [16].

Effective moisture diffusivity (D_{eff}), generally expressed in $\text{m}^2 \text{s}^{-1}$, describes the combined effect of internal moisture-transfer mechanisms and is commonly estimated from Fick's second law of diffusion. For a simplified slab geometry, the long-time solution is (Wang *et al.*, 2022; Yogendrasasidhar *et al.*, 2018; do Nascimento *et al.*, 2015; Srinivasakannan *et al.*, 2009; Ramakrishnan *et al.*, 2025) [6, 7, 14, 16, 17]

$$MR = (8/\pi (Satyavathi \text{ et al.}, 2021)^{[2]}) \exp[-(\pi (Satyavathi \text{ et al.}, 2021)^{[2]} D_{\text{eff}} t) / (4L (Satyavathi \text{ et al.}, 2021)^{[2]})]$$

where t is drying time and L the characteristic half-thickness. Higher D_{eff} indicates faster internal moisture movement, but the parameter is sensitive to temperature, moisture content, structure, pretreatment and geometry; drying studies on foxtail millet confirm that D_{eff} varies with drying method (Wang *et al.*, 2022) [6], while fluidized-bed studies on Kodo and barnyard millet show that drying conditions influence both moisture transfer and energy requirement (Yogendrasasidhar *et al.*, 2018; Yogendrasasidhar *et al.*, 2019) [7, 8]. Work on finger millet has reported a curvilinear falling-rate pattern with D_{eff} increasing with drying temperature and airflow velocity (do Nascimento *et al.*, 2015; Srinivasakannan *et al.*, 2009) [14, 16].

The major factors controlling millet drying are drying temperature, air velocity, relative humidity, initial moisture content, particle or grain size, bed depth, loading density and pretreatment. Higher temperature increases the vapour-pressure driving force and accelerates moisture migration, but excessive temperature can damage nutritional and functional quality; air velocity governs external heat and mass transfer resistance, relative humidity sets the moisture-carrying capacity of the drying air, and product thickness and loading affect airflow distribution and drying uniformity. Effective drying of millet-based foods therefore requires a balance between rapid moisture removal, energy consumption and retention of desirable quality — the foundation on which conventional, novel and hybrid drying technologies must be developed and optimised (Jimoh *et al.*, 2023; do Nascimento *et al.*, 2015; Srinivasakannan *et al.*, 2009) [13, 14, 16].

4. Conventional drying technologies and their limitations

Conventional methods for reducing the moisture content of millet grains and products include sun drying, natural-air drying, hot-air (convective) drying, cabinet/tray drying and fluidized-bed drying. Hot-air drying is the most common mechanical method because it is comparatively simple to operate and provides controlled conditions; heated air is passed over or through the product, transferring heat while removing moisture (Jimoh *et al.*, 2023) [13].

Sun drying, the simplest and least expensive method for agricultural commodities, spreads grain in a thin layer for direct solar exposure, but is strongly dependent on solar radiation, temperature, humidity and wind, making drying slow and non-uniform under cloudy or humid conditions and increasing the risk of contamination by dust, insects and other foreign material (Yu *et al.*, 2025) [18]. Natural-air drying, using ambient or slightly heated air, requires simple equipment but has a low drying rate because of the limited moisture-carrying capacity of ambient air; longer drying periods increase the risk of mould growth if drying is inadequate (Jimoh *et al.*, 2023; Yu *et al.*, 2025) [13, 18]. Hot-air or convective drying provides better control of temperature, air velocity and time and is therefore suited to large-scale, controlled processing, but requires considerable thermal energy for continuous air heating and evaporation of the latent heat of water, and long drying times together with exhaust-air heat losses further raise energy consumption; high temperatures can also damage colour, texture, starch characteristics and heat-sensitive nutritional or bioactive components (Jimoh *et al.*, 2023; Zahoor *et al.*, 2023) [13, 19]. Cabinet or tray drying, common at laboratory and small-to-medium scale, offers better control than open-air drying but can suffer from non-uniform

form air velocity and temperature within the chamber, so tray loading, bed thickness and product arrangement require careful control (Yu *et al.*, 2025) [18]. Fluidized-bed drying provides good contact between heated air and individual grains, enhancing heat and mass transfer and enabling relatively rapid moisture removal, though higher airflow requirements, equipment complexity and energy consumption can limit its use depending on product and scale (do Nascimento *et al.*, 2015; Srinivasakannan *et al.*, 2009) [14, 16].

Overall, conventional methods offer simple, established approaches to moisture removal but face limitations in energy consumption, drying time, moisture non-uniformity, heat-induced quality loss and dependence on environmental conditions — limitations that have driven the development of novel and hybrid drying technologies capable of improving efficiency while better maintaining nutritional, functional and sensory quality (Jimoh *et al.*, 2023; Zahoor *et al.*, 2023) [13, 19].

5. Novel drying and dehydration technologies

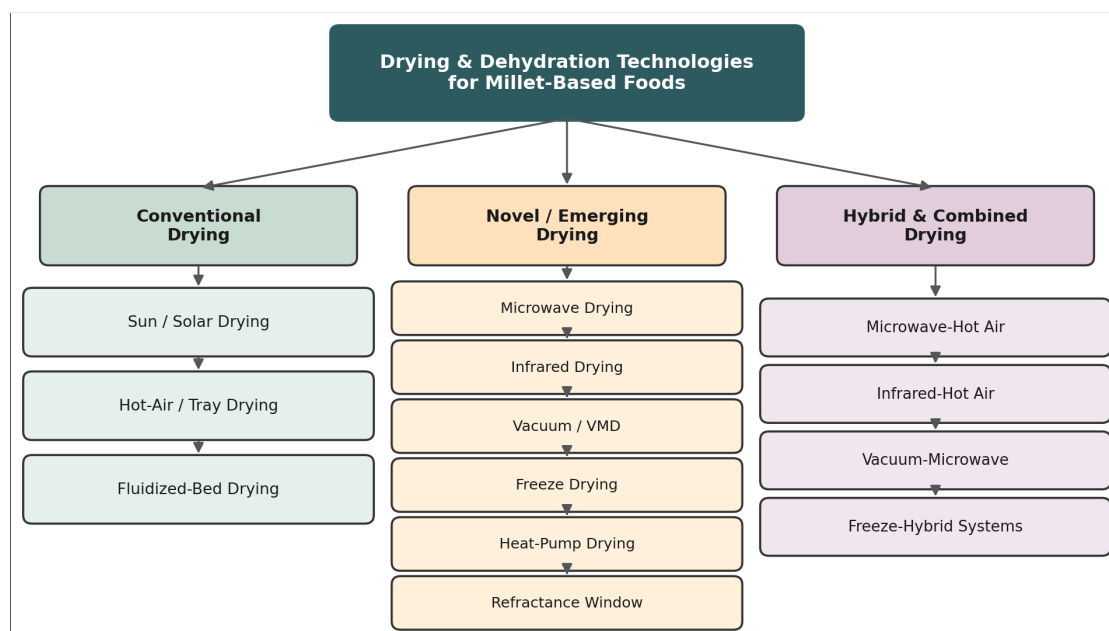


Figure 1. Classification of drying and dehydration technologies applicable to millet-based foods.

The limitations of conventional drying — high energy consumption, long drying time, non-uniform moisture removal and deterioration of heat-sensitive attributes — have encouraged development of novel drying and dehydration technologies that modify heat and mass transfer within the food to improve drying rate, energy efficiency and product quality. Important technologies include microwave, infrared, vacuum, freeze, heat-pump, Refractance Window and hybrid or combined drying systems (Zahoor *et al.*, 2023; Zhang *et al.*, 2024) [19, 20]. Technology selection depends on the moisture content, physical structure, thickness, composition and intended use of the product [21], and is especially relevant for millet-based foods because drying influences starch properties, colour, texture, nutrients, phenolics, antioxidant activity, rehydration behaviour and functional properties. Development of novel drying systems should therefore weigh energy consumption and product quality alongside drying-time reduction.

5.1 Microwave drying

Microwave drying converts electromagnetic energy into heat within the food. Unlike conventional hot-air drying, where heat moves from the surface inward, microwave energy produces volumetric heating because water molecules and other polar components couple with the electromagnetic field, promoting rapid internal heating and accelerated moisture migration (Zahoor *et al.*, 2023; Dehghannya *et al.*, 2025) [19, 22]. This is particularly valuable in the falling-rate period, when internal moisture movement is the principal resistance to drying, allowing rapid moisture removal with shorter external heating exposure. Microwave drying has potential application to millet grains, flour-based products, germinated millet and porridge powders, and can be combined with other methods for improved process control: microwave-assisted hot-air drying couples volumetric heating with convective moisture removal; microwave–vacuum drying allows heating under reduced pressure to facilitate evaporation at lower temperature; microwave–infrared systems combine internal volumetric

heating with surface radiation; and microwave-assisted fluidized-bed drying can improve heat and mass transfer around individual particles (Zahoor *et al.*, 2023; Dehghannya *et al.*, 2025) [19, 22]. Non-uniform heating remains a major limitation — differences in moisture content, geometry, dielectric properties and load distribution can produce hot and cold spots, and excessive power can cause localised overheating and textural damage — so microwave power, load, layer thickness, exposure time and temperature require careful control (Zahoor *et al.*, 2023) [19]. Field-distribution complexity also increases with chamber size and load, making scale-up an important challenge that requires further optimisation of power and heating uniformity before wider industrial use (Zahoor *et al.*, 2023; Dehghannya *et al.*, 2025) [19, 22].

5.2 Microwave-assisted hot-air drying

In this hybrid technology, microwave energy supplies internal heat while hot air removes moisture at the product surface, overcoming some limitations of each method used alone: microwave energy accelerates internal moisture movement while hot air maintains continuous surface moisture removal (Zahoor *et al.*, 2023) [19]. For millet-based products this combination can reduce drying time and improve energy utilisation relative to conventional hot-air drying without requiring excessive microwave power, though final quality depends on the balance between microwave power, air temperature, air velocity and product loading — excessive power risks overheating, while insufficient power gives only limited benefit. The approach is especially useful for accelerating the slow, diffusion-limited final stage of drying while hot air controls surface conditions, potentially reducing total thermal exposure and improving process flexibility (Zahoor *et al.*, 2023; Zhang *et al.*, 2024) [19, 20]. Recent energy analyses identify microwave-containing hybrid systems as important options for improving drying efficiency, though performance remains product- and equipment-dependent (Zhang *et al.*, 2024) [20].

5.3 Infrared drying

Infrared (IR) drying transfers electromagnetic radiation directly to the product surface, where it is absorbed and converted to thermal energy; compared with conventional hot-air heating it can provide rapid surface heating and integrates readily with convective, vacuum and microwave systems (Huang *et al.*, 2021) [23]. Advantages include rapid heating, short drying time, easy temperature control and reduced energy loss from heating large air volumes, with effectiveness depending on radiation intensity, wavelength, emitter-product distance, product thickness, moisture content and temperature (Huang *et al.*, 2021; Pawar *et al.*, 2017) [23, 24]. For millet-based products, IR drying suits grains, flakes and thin-layer ingredients, since radiation is absorbed near the surface and rapidly raises product temperature; combining IR with hot air improves moisture removal by adding radiative heating to convective vapour removal (Huang *et al.*, 2021) [23]. Excessive intensity or too short an emitter distance can cause overheating, so conditions must match product thickness and moisture content, and the relationship between IR power and energy consumption is not always linear—energy use falls only when the reduction in drying time is substantial (Pawar *et al.*, 2017) [24].

5.4 Infrared-assisted hot-air and hybrid infrared drying

Infrared can be combined with hot air, microwave, vacuum or freeze drying to improve overall performance. In infrared-hot-air drying, radiation supplies additional heat while hot air removes evaporated moisture, improving drying kinetics over convection alone. Infrared-microwave drying combines near-surface radiative heating with volumetric electromagnetic heating in a complementary manner, while infrared-vacuum drying can lower the temperature required for evaporation. Because millet products may contain heat-sensitive nutrients and bioactive compounds, these hybrid systems are relevant for shortening thermal exposure while product temperature, IR intensity and exposure time remain carefully controlled (Huang *et al.*, 2021; Pawar *et al.*, 2017) [23, 24].

5.5 Vacuum drying

Vacuum drying is carried out under reduced pressure, which lowers the boiling point of water and allows evaporation at lower product temperature than under atmospheric conditions, making it suitable for heat-sensitive nutrients, flavours and bioactive compounds (Zhang *et al.*, 2024; AlZohbi *et al.*, 2026) [20, 25]. Reduced pressure increases the driving force for moisture removal and limits oxidation by reducing surrounding oxygen, helping preserve colour, flavour and certain nutrients — properties relevant to high-value millet ingredients. However, vacuum drying requires a sealed chamber, vacuum pump and control systems, raising equipment complexity and capital cost relative to hot-air drying, and heat-transfer rate can be limited depending on the heating arrangement and product structure (AlZohbi *et al.*, 2026) [25]. Pulsed vacuum drying, in which pressure is cycled between vacuum and atmospheric or higher pressure, modifies internal moisture transport and has been investigated for reducing drying time and energy consumption while improving colour, texture and nutritional retention (Zhang *et al.*, 2024) [20].

5.6 Vacuum microwave drying

Vacuum microwave drying combines microwave volumetric heating with evaporation under reduced pressure: the microwave field supplies energy directly to the material while the vacuum lowers the boiling temperature of water, allowing rapid moisture removal without very high product temperatures (Gonzalez-Cavieres *et al.*, 2021) [26]. This combination is well suited to heat-sensitive foods, shortening drying time and thermal exposure while the internal pressure generated by microwave heating promotes moisture movement through the matrix. For millet-based products it may benefit high-value ingredients, germinated millet products and applications where colour, flavour and bioactive retention are important, although electrical properties, microwave power, chamber pressure, product thickness

and load distribution require careful control, and uneven heating and equipment complexity remain significant challenges (Gonzalez-Cavieres *et al.*, 2021) [26].

5.7 Freeze drying

Freeze drying (lyophilization) removes water from a previously frozen product under vacuum, converting ice directly to vapour by sublimation, followed by secondary drying to remove remaining bound moisture. Because the process occurs at low temperature and reduced pressure, it retains many heat-sensitive nutritional, structural and sensory characteristics (Uwineza *et al.*, 2026) [27]. Ice-crystal formation followed by sublimation produces a porous structure with good rehydration behaviour, and colour, flavour, nutrients and bioactive compounds are typically better preserved than in high-temperature drying (Uwineza *et al.*, 2026; Nwankwo *et al.*, 2023) [27, 28]. Freeze drying therefore suits high-value millet-based products such as functional ingredients, germinated millet, infant-food ingredients and products with heat-sensitive bioactive compounds, but freezing and vacuum maintenance require substantial energy, the process is relatively slow, and capital and operating costs are high, so it may be better suited to premium products than bulk commodities (Uwineza *et al.*, 2026) [27]. Physical-field assistance — microwave, infrared, ultrasound and pulsed electric field technologies — is being explored to increase drying rate and reduce energy consumption while retaining freeze-drying's quality advantages (Uwineza *et al.*, 2026; Nwankwo *et al.*, 2023) [27, 28].

5.8 Heat-pump drying

Heat-pump drying is a low-temperature technology that uses a refrigeration cycle to remove moisture from the drying air and recover heat, typically operating as a closed or semi-closed loop with recirculated, dehumidified air. Because moisture condenses out of the air, drying can proceed at relatively low temperature under controlled humidity (Sun *et al.*, 2025) [29]. Advantages include improved energy utilisation, controlled drying conditions and suitability for heat-sensitive materials, since low relative humidity provides a strong moisture-removal driving force even at moderate temperature, helping preserve colour, nutrients and functional properties (Sun *et al.*, 2025; Uthpala *et al.*, 2020) [29, 30]. Heat-pump drying is potentially applicable to millet grains, flakes and flour-based ingredients where controlled low-temperature drying is preferable to the shortest possible drying time, though refrigeration components, heat exchangers, compressors and controls add equipment complexity, and performance depends on ambient conditions, air circulation, loading and operating temperature range. Continued optimisation of system configuration, heat recovery and operating conditions is needed for wider industrial application (Sun *et al.*, 2025; Uthpala *et al.*, 2020) [29, 30]. (Sun *et al.*, 2025; Uthpala *et al.*, 2020) [29, 30]

5.9 Refractance window drying

Refractance Window Drying (RWD) is a thin-layer technology suited to liquid, semi-liquid, purée and slurry materials, in which the product is spread as a thin layer on a transparent polymer film above a hot-water bath, with thermal energy transferred through the film by conduction, convection and radiation (Mahanti *et al.*, 2021) [31]. Product temperature remains substantially lower than the water temperature because of this transfer mechanism and the changing optical properties of the product during drying, making RWD attractive for heat-sensitive nutrients, pigments and bioactive compounds; applications have been reported for juices, purées and other heat-sensitive foods (Mahanti *et al.*, 2021) [31]. For millet-based foods, RWD could be relevant to porridges, slurries, purées and formulated liquid products rather than whole grains, offering rapid moisture removal with good colour, functional and nutritional retention, though it requires suitable feed consistency and controlled layer thickness, and commercial-scale equipment design remains an area for further work (Mahanti *et al.*, 2021) [31].

6. Hybrid and combined drying technologies

Hybrid drying combines two or more methods in a single process to capture complementary advantages while reducing individual limitations — examples include microwave–hot-air, microwave–vacuum, infrared–hot-air, infrared–microwave, infrared–vacuum, microwave–freeze and solar–heat-pump drying [21, 22, 28]. Because different energy-transfer mechanisms operate simultaneously or sequentially, hybrid drying can improve kinetics: microwave energy accelerates internal moisture movement while hot air clears the surface; infrared provides rapid surface heating while microwave energy promotes internal heating; and in microwave–vacuum drying, reduced pressure lowers the evaporation temperature while microwave energy supplies internal heat (Zahoor *et al.*, 2023; Gonzalez-Cavieles *et al.*, 2021) [19, 26]. Hybrid freeze-drying systems have attracted particular interest — microwave-assisted freeze drying can supply energy directly to the frozen material and accelerate sublimation, infrared-assisted freeze drying adds radiant energy, and ultrasound-assisted systems modify moisture transport — aiming to reduce the long processing time and high energy demand of conventional freeze drying (Nwankwo *et al.*, 2023) [28]. The principal challenge in hybrid drying is process optimisation: combining two technologies does not automatically lower energy consumption or improve quality, and operating parameters of both systems must be balanced to the food's characteristics, while equipment integration, control systems, investment and maintenance requirements grow with system complexity (An *et al.*, 2024; Nwankwo *et al.*, 2023) [21, 28]. (An *et al.*, 2024; Dehghannya *et al.*, 2025; Nwankwo *et al.*, 2023; Kusuma *et al.*, 2026) [21, 22, 28, 32]

7. Emerging technologies and process intensification

Several additional approaches are being investigated for food dehydration, including ultrasound-assisted drying, radio-frequency drying, electrohydrodynamic drying, pulsed electric field-assisted drying and superheated-steam drying, which aim to improve moisture transport by modifying food structure, increasing internal heating or reducing mass-transfer resistance. Ultrasound generates mechanical effects that influence moisture migration and can be integrated with vacuum or other drying methods; radio-frequency heating offers volumetric electromagnetic heating at lower frequency than microwaves, potentially with deeper penetration; and electrohydrodynamic drying uses electric fields and ion wind to enhance surface moisture removal. These technologies remain at different stages of development, and their industrial adoption depends on equipment cost, process reliability, safety, energy performance and scale-up [21, 32]. For millet-based foods, emerging technologies should be judged not only on drying time but on specific energy consumption, effective moisture diffusivity, colour, nutritional retention, starch functionality, rehydration, sensory quality and storage stability, since rapid drying does not necessarily guarantee desirable quality or economic performance.

8. Selection of novel drying technology for millet-based foods

Technology selection depends on the physical form and intended application of the millet product. Whole grains require technologies capable of moving moisture effectively through the grain structure, whereas flour, porridge and slurry products are often better suited to thin-layer, vacuum or Refractance Window systems. Heat-sensitive functional ingredients may benefit from low-temperature vacuum, heat-pump or freeze drying; microwave and infrared technologies suit applications requiring rapid drying; and heat-pump drying is preferable where controlled low-temperature operation and energy recovery matter. Freeze drying gives high-quality products but is often restricted to high-value applications given its energy and equipment demands, while hybrid systems can balance drying rate, energy consumption and quality at the cost of greater equipment complexity (An *et al.*, 2024; Sun *et al.*, 2025) [21, 29]. Development of novel millet-drying technologies should therefore follow a product- and application-specific approach that integrates drying kinetics, heat and mass

transfer, energy and exergy analysis, nutritional and bioactive retention, sensory properties and economic feasibility; no single technology is universally suitable, and selection should reflect the interaction between product properties, process conditions, energy requirements and desired quality [21, 30].

9. Effect of drying technologies on nutritional quality

Drying is essential for preserving millet-based foods, but heat and process duration can influence nutritional quality; the extent of change depends on drying temperature, time, moisture content, heating method, product thickness and millet type. Proteins, carbohydrates, dietary fibre and minerals are generally more stable than heat-sensitive vitamins and certain bioactive compounds, so selecting an appropriate technology is important for adequate moisture removal with minimal nutritional loss (Kabeer *et al.*, 2023; Wang *et al.*, 2022; Pasha *et al.*, 2018) [5, 6, 33]. (Kabeer *et al.*, 2023; Wang *et al.*, 2022; Pasha *et al.*, 2018; Devi *et al.*, 2014) [5, 6, 33, 34]

Moderate drying has limited effect on total protein and carbohydrate content, but high temperature and prolonged heating can cause protein denaturation, Maillard reactions and starch changes that influence digestibility, water absorption and pasting behaviour. (Wang *et al.*) [9] reported that hot-air and microwave drying of gelatinized foxtail millet affected starch crystallinity and swelling, demonstrating that drying conditions influence functional and eating quality. Dietary fibre and minerals are relatively heat-stable, though measured concentrations can shift with moisture removal and structural change; microwave drying of sprouted little millet, particularly at higher power, increased measured dietary fibre and improved bioavailability of iron and calcium while reducing tannins and phytate (Jena *et al.*, 2025) [10], indicating that drying should be evaluated together with antinutritional-compound and mineral-bioavailability changes rather than nutrient concentration alone.

Water-soluble vitamins are more susceptible to thermal degradation than minerals, proteins and fibre, with loss depending mainly on temperature and exposure time; low-temperature methods such as freeze, vacuum or heat-pump drying can therefore better retain heat-sensitive nutrients. (Kabeer *et al.*) [5], comparing spray, tray and freeze drying of finger millet porridge powder, reported that freeze-dried samples retained calcium, iron and B-group vitamins particularly well, underscoring the potential of low-temperature drying for nutrient-sensitive millet products.

Phenolic compounds and other antioxidants contribute to the functional value of millets but can be affected by drying temperature and duration; severe thermal treatment may degrade heat-sensitive phenolics, while suitable conditions can improve extractability by disrupting the food matrix. Drying can also influence antinutritional factors such as phytate and tannins — (Jena *et al.*) [10] found that sprouting followed by microwave drying reduced condensed tannin and phytate content and improved the nutritional and functional characteristics of little millet flour. Overall, conventional hot-air drying is simple but requires longer heat exposure; microwave and microwave-assisted drying can shorten processing time and thermal exposure, though excessive power risks localised overheating; and freeze drying gives good nutrient retention at higher energy and equipment cost. The optimal technology should therefore be matched to the millet product and the nutritional or functional attributes that must be retained, with future work optimising temperature, time, microwave power, vacuum pressure and hybrid drying conditions to maximise nutrient and bioactive retention.

10. Effect on bioactive compounds and functional properties

Drying influences the concentration, stability, extractability and bioavailability of the phenolic compounds, flavonoids, tannins, dietary fibre and other phytochemicals responsible for millet's antioxidant activity and functional properties (Saleh *et al.*, 2013; Anju *et al.*, 2021) [1, 3]. The degree of change depends mainly on temperature,

drying time, moisture content, heating mechanism and product form. Phenolic compounds are relatively sensitive to prolonged thermal exposure, and high-temperature hot-air drying can reduce some phenolics through oxidation and degradation; drying can also disrupt plant-cell structure and improve release of bound phenolics, so the net effect on measured antioxidant activity is not always a simple loss and depends on both operating conditions and analytical method (Anju *et al.*, 2021; Devi *et al.*, 2014) [3, 34]. Rapid technologies such as microwave and infrared drying shorten thermal exposure and can therefore help retain bioactive compounds when properly optimised (Zahoor *et al.*, 2023; Huang *et al.*, 2021) [19, 23].

Antinutritional compounds such as phytate and tannins reduce mineral and protein bioavailability; appropriate processing can lower these compounds and improve functional and nutritional quality. (Jena *et al.*) [10] found that sprouting followed by microwave drying reduced condensed tannin and phytate content in little millet flour while improving certain mineral-related and functional characteristics, showing that suitable drying conditions combined with pretreatment can improve, not just preserve, ingredient quality. Drying also affects water absorption, swelling, solubility and pasting behaviour of millet flours and powders through changes in starch, protein and fibre interactions; (Wang *et al.*) [9] observed altered starch crystallinity and eating-related properties in dried, gelatinized foxtail millet, and drying conditions similarly influence rehydration and water-holding behaviour (Wang *et al.*, 2022) [6]. Excessive thermal treatment can cause undesirable structural change, whereas optimised drying can yield powders with functional properties suited to instant foods, porridges, bakery products and other formulations. Future studies should evaluate individual bioactive compounds, their bioaccessibility and functional performance rather than total phenolic content and antioxidant activity alone, while controlling temperature, microwave power, drying time, moisture level and product thickness to avoid the localised overheating that can offset the benefits of shorter drying time.

11. Energy efficiency and sustainability

Drying is generally energy-intensive, since substantial energy is required to heat the drying medium, evaporate moisture and remove water vapour; the requirement depends on initial and final moisture content, drying temperature, air velocity, relative humidity, product loading, drying time and equipment efficiency (Jimoh *et al.*, 2023; Yu *et al.*, 2025) [13, 18]. Improving energy efficiency while maintaining quality is therefore essential for sustainable millet processing.

In conventional hot-air drying, energy is consumed mainly in heating air and sustaining the required temperature for a relatively long period, with poor insulation, heat losses and inefficient moisture removal further raising consumption. Specific energy consumption (SEC) — the energy required per unit mass of water removed — is a useful comparison parameter, and energy and exergy analyses help identify major loss sources and guide equipment design and operation (Yogendrasasidhar *et al.*, 2018; Yogendrasasidhar *et al.*, 2019; Zhang *et al.*, 2024) [7, 8, 20]. Fluidized-bed drying can provide efficient heat and mass transfer through good air-product contact, though fan power and equipment requirements must also be weighed.

Novel technologies can reduce energy consumption by increasing moisture-removal rate or shortening thermal treatment: microwave drying produces volumetric heating that can substantially shorten drying time (Zahoor *et al.*, 2023; Dehghannya *et al.*, 2025) [19, 22]; infrared drying transfers energy directly to the surface with reduced heat loss under suitable conditions (Huang *et al.*, 2021; Pawar *et al.*, 2017) [23, 24]; and heat-pump drying is particularly promising because its closed or semi-closed air cycle can recover heat from the drying air, with low-temperature operation additionally suiting quality-sensitive products (Sun *et al.*, 2025; Uthpala *et al.*, 2020) [29, 30]. The realised energy advantage, however, depends on equipment design, operating conditions, product loading and system efficiency.

Sustainable drying should weigh energy consumption together with product quality, environmental impact, equipment cost and productivity. Renewable energy sources such as solar power can reduce depen-

dence on fossil-fuel-based energy, particularly for decentralised millet processing, and hybrid systems combining solar energy with heat pumps, microwave, infrared or conventional heating may provide more stable drying conditions while lowering energy demand, although the additional equipment and control requirements must be considered in techno-economic evaluation (Jimoh *et al.*, 2023; AlZohbi *et al.*, 2026) [13, 25]. Parameters such as SEC, energy efficiency, exergy efficiency, drying time and product quality should be assessed together rather than relying on drying time alone; future research should prioritise optimised hybrid systems, improved insulation, heat recovery, renewable-energy integration, intelligent process control and scale-up studies to develop economically and environmentally sustainable millet-drying systems (An *et al.*, 2024; AlZohbi *et al.*, 2026) [21, 25].

12. Quality, storage stability and rehydration behaviour

Product quality after drying is determined not only by the efficiency of moisture removal but also by physical, nutritional, functional and sensory characteristics, all of which can be influenced by drying conditions (Kabeer *et al.*, 2023; Wang *et al.*, 2022; Jimoh *et al.*, 2023) [5, 6, 13].

Colour is an important quality attribute, since excessive heating can promote enzymatic and non-enzymatic browning; texture changes can also occur through moisture removal, starch modification and structural collapse. (Wang *et al.*) [9] reported that drying conditions affected starch crystallinity and eating quality in gelatinized foxtail millet. Rapid methods such as microwave and infrared drying can shorten drying time, but non-uniform heating may cause localised overheating and quality variation if not properly controlled (Zahoor *et al.*, 2023; Huang *et al.*, 2021) [19, 23], so temperature, heating intensity, product thickness and drying time should be optimised for uniform quality.

Storage stability depends strongly on final moisture content and water activity: adequate drying limits water available for microbial growth and slows chemical and enzymatic reactions, but dried products can reabsorb moisture from the environment if packaging offers inadequate moisture-barrier protection, leading to loss of crispness, caking, microbial deterioration and altered functional properties. Dried millet products should therefore be cooled before packaging and stored under controlled temperature and humidity in suitable moisture-resistant packaging, guided by moisture sorption behaviour (do Nascimento *et al.*, 2015; Goneli *et al.*, 2010) [14, 15].

Rehydration performance is a key quality indicator for instant millet products, porridge powders and precooked products; a well-dried product should absorb water rapidly and recover texture and appearance with minimal structural damage. Rehydration capacity depends on drying temperature, drying rate, porosity, particle size, initial moisture content and structural change during drying — excessive heating can collapse structure or cause irreversible starch and protein changes that reduce water absorption, while appropriate drying can produce a porous structure that facilitates rapid rehydration. (Wang *et al.*) [6] demonstrated that drying method influenced the physicochemical and sensory properties of instant foxtail millet, underlining the role of drying conditions in determining reconstituted-product performance. Overall quality assessment should combine colour, texture, moisture content, water activity, rehydration ratio, nutritional retention, antioxidant activity and sensory acceptability, evaluated both immediately after drying and during storage, so that effective drying technologies can be identified as those achieving sufficient moisture removal while maintaining desirable physical, nutritional and functional characteristics.

13. Scale-up and industrial challenges

Translating novel drying technologies from laboratory to pilot and industrial scale requires systematic evaluation of drying kinetics, energy consumption, product quality and equipment performance, since labo-

ratory-scale results cannot always be reproduced at larger scale once product loading, equipment geometry, airflow, heat distribution and operating conditions change (Jimoh *et al.*, 2023; Yu *et al.*, 2025) [13, 18]. (Jimoh *et al.*, 2023; Yu *et al.*, 2025; Dehghannya *et al.*, 2025; Huang *et al.*, 2021; Kusuma *et al.*, 2026; Ramakrishnan *et al.*, 2025) [13, 18, 22, 23, 32, 17]

Achieving uniform heating and moisture removal across a large product bed is a major challenge: non-uniform airflow and bed-depth variation in conventional hot-air and fluidized-bed systems can create drying-rate differences across the dryer, microwave fields can become non-uniform in larger chambers and produce hot spots (Zahoor *et al.*, 2023; Dehghannya *et al.*, 2025) [19, 22], and infrared radiation intensity can vary with source-to-surface distance (Huang *et al.*, 2021; Pawar *et al.*, 2017) [23, 24]. Equipment geometry, airflow distribution, heating-source arrangement and product loading must therefore be carefully designed. Industrial drying also requires considerable energy, and economic feasibility depends on both energy consumption and processing capacity; specific energy consumption, energy efficiency, drying time and throughput should all be evaluated during scale-up (Yogendrasasidhar *et al.*, 2018; Yogendrasasidhar *et al.*, 2019; Zhang *et al.*, 2024) [7, 8, 20]. Technologies such as microwave, heat-pump and hybrid drying may shorten drying time or improve energy utilisation, but higher initial equipment and control costs can affect economic feasibility, so techno-economic assessment should cover capital cost, operating cost, maintenance, energy requirement, labour and product yield.

Large-scale systems require accurate control of temperature, humidity, airflow, microwave power, vacuum pressure or infrared intensity depending on the technology used; automated sensors and feedback control can improve consistency and uniformity, though increased automation adds system complexity and investment. Industrial-scale processing must also maintain nutritional quality, colour, texture, bioactive compounds and rehydration properties while achieving the required moisture level (Kabeer *et al.*, 2023; Wang *et al.*, 2022; Jena *et al.*, 2025) [5, 6, 10]. Variation in millet variety, grain size, initial moisture content, particle size, maturity and pretreatment further means that a single drying condition may not suit all millet-based products, so industrial dryers should have sufficient flexibility to accommodate raw-material and formulation variability, and pilot-scale studies under different loading conditions remain essential before commercial implementation. Successful scale-up therefore requires integrating heat and mass transfer principles, equipment design, energy analysis, process control, product quality and economic evaluation, with future work focused on pilot-scale validation, computational modelling, intelligent process control, heat recovery, renewable-energy integration and standardised performance indicators (Yu *et al.*, 2025; An *et al.*, 2024; AlZohbi *et al.*, 2026) [18, 21, 25].

14. Comparative evaluation of drying technologies

No single drying method suits all millet-based foods; selection should be based on product form, desired final moisture content, required quality, processing capacity, energy availability and economic feasibility (Jimoh *et al.*, 2023; Yu *et al.*, 2025; AlZohbi *et al.*, 2026) [13, 18, 25]. Sun and natural-air drying require the least equipment investment but depend strongly on weather and generally require longer drying periods, with the added risk of contamination by dust and insects; hot-air tray or cabinet drying offers better temperature and hygiene control but demands considerable energy for prolonged heating; and fluidized-bed drying improves contact between air and product for relatively rapid drying but adds fan-power and equipment complexity (Yogendrasasidhar *et al.*, 2018; Yogendrasasidhar *et al.*, 2019; Srinivasakannan *et al.*, 2009; Yu *et al.*, 2025) [7, 8, 16, 18].

Among novel technologies, microwave drying offers rapid volumetric heating and substantial time savings but can suffer from non-uniform electromagnetic fields and hot spots during scale-up (Zahoor *et al.*, 2023; Dehghannya *et al.*, 2025) [19, 22]. Infrared drying provides direct radiant heating and rapid surface moisture removal, useful for thin layers and suitable products (Huang *et al.*, 2021; Pawar *et al.*,

2017) [23, 24]. Vacuum drying promotes moisture removal at lower temperature, benefiting heat-sensitive compounds, and vacuum microwave drying combines reduced-pressure drying with volumetric heating for rapid drying with improved quality retention, though at higher equipment cost and process-control demand (Zhang *et al.*, 2024; Gonzalez-Cavieles *et al.*, 2021) [20, 26]. Freeze drying gives excellent retention of colour, structure and sensitive nutrients but is limited for bulk, low-cost products by its energy requirement, long processing time and equipment cost (Uwineza *et al.*, 2026; Nwankwo *et al.*, 2023) [27, 28]. Heat-pump drying operates at relatively low temperature and recovers energy from the drying air, making it attractive on both energy-efficiency and quality grounds (Sun *et al.*, 2025; Uthpala *et al.*, 2020) [29, 30]. Refractance Window drying suits liquid, purée and slurry-type foods but is more limited for whole grains and thick solid millet products (Mahanti *et al.*, 2021) [31]. Hybrid technologies — microwave-hot-air, infrared-hot-air and microwave-vacuum among them — attempt to combine the advantages of individual technologies while reducing their limitations (An *et al.*, 2024; Dehghannya *et al.*, 2025) [21, 22].

Comparative performance should be assessed using multiple parameters together — drying time, specific energy consumption, energy and exergy efficiency, moisture uniformity, nutrient and bioactive retention, colour, texture, rehydration, equipment cost and scalability — since rapid drying alone does not guarantee better performance if heating is excessive or non-uniform. The most appropriate technology for millet-based foods should therefore be selected through balanced assessment of drying performance, energy efficiency, product quality, economic feasibility and industrial scalability, with future work emphasising optimised hybrid systems and pilot-scale validation to identify conditions that minimise quality loss while maintaining efficient moisture removal (An *et al.*, 2024; AlZohbi *et al.*, 2026) [21, 25].

15. Research gaps and future perspectives

Despite considerable progress, several research gaps remain in applying novel drying technologies to millet-based foods. Existing studies have concentrated mainly on drying kinetics, moisture removal and selected quality parameters, while integrated evaluation of energy efficiency, nutritional quality, bioactive compounds, storage stability and economic feasibility remains comparatively limited (Jimoh *et al.*, 2023; An *et al.*, 2024; AlZohbi *et al.*, 2026) [13, 21, 25].

Different millet varieties and product forms exhibit distinct moisture characteristics, particle sizes, compositions and drying behaviour, so conditions developed for one millet cannot be assumed to transfer directly to another. Future studies should establish optimum temperature, air velocity, microwave power, infrared intensity, vacuum pressure, product thickness and loading density for individual millet products, combining mathematical modelling and drying kinetics with quality assessment to identify optimum processing conditions (do Nascimento *et al.*, 2015; Zahoor *et al.*, 2023; Ramakrishnan *et al.*, 2025) [14, 19, 17]. Many studies report drying time and final moisture content without comprehensive energy or environmental data; future work should evaluate specific energy consumption, energy and exergy efficiency, drying rate and product quality simultaneously, incorporating life-cycle assessment and techno-economic analysis to determine commercial-scale environmental and economic feasibility [21, 25].

Hybrid drying technologies — microwave-hot-air, infrared-hot-air, vacuum-microwave and heat-pump-assisted systems — can potentially improve drying rate and energy utilisation while reducing thermal damage (Dehghannya *et al.*, 2025; Gonzalez-Cavieles *et al.*, 2021; Sun *et al.*, 2025) [22, 26, 29], but the optimum combination of technologies and operating conditions requires further investigation. Integrating sensors, machine learning, digital monitoring and automated feedback control could help regulate temperature, moisture and energy input according to real-time product conditions. A major gap is the limited availability of pilot- and industrial-scale studies, since airflow distribution, electromagnetic field uniformity, product loading and heat-transfer characteristics change with equipment size and laboratory results may not represent industrial performance (Yu *et al.*,

2025; Dehghannya *et al.*, 2025; Huang *et al.*, 2021) [18, 22, 23]; future studies should therefore include pilot-scale validation, equipment optimisation, continuous operation and assessment of throughput and product uniformity. Research should also extend beyond dried grains and powders toward value-added products such as instant porridges, ready-to-cook foods, extruded products, bakery ingredients and functional formulations, evaluating bioaccessibility of nutrients and bioactive compounds rather than total concentration alone, and incorporating storage stability, rehydration behaviour, sensory acceptability and consumer requirements into technology evaluation. Standardised reporting of drying conditions, energy indicators, quality parameters and economic performance would improve comparability across studies and facilitate transfer from laboratory research to commercial millet-based food production.

16. Conclusion

Novel drying and dehydration technologies offer important opportunities to improve the efficiency, quality and sustainability of millet-based food processing. Conventional methods such as sun, tray and hot-air drying are simple and widely applicable but often require longer drying times and considerable energy, with attendant risks to nutritional, functional and sensory quality. Novel technologies — microwave, infrared, vacuum, freeze and heat-pump drying — can improve moisture removal and, under optimised conditions, reduce drying time and thermal exposure, though overall performance depends on the interaction between drying rate, energy consumption, product quality and processing cost rather than drying-time reduction alone. Nutritional components, bioactive compounds, colour, texture, storage stability and rehydration behaviour must all be considered, and hybrid systems offer further potential by combining different heat and mass transfer mechanisms to improve process efficiency and product quality. Important challenges remain, however, in achieving uniform drying, reducing energy consumption, controlling process conditions and transferring laboratory-scale technologies to industrial production. Future research should focus on pilot- and industrial-scale validation, energy and exergy analysis, techno-economic assessment, renewable-energy integration, heat recovery and intelligent process control. Development of energy-efficient, quality-oriented and scalable drying systems along these lines can support sustainable processing and wider utilisation of millet-based foods.

Acknowledgement

The authors are grateful to DSLD college of Horticultural Engineering and Food Technology, University of Horticultural Sciences, Bagalkot.

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How to cite this article: Sneha R, Patil NA, Sneha A, LP V. Novel drying and dehydration technologies for millet-based foods: Energy efficiency, quality retention and scale-up challenges. *International Journal of Research in Agronomy.* 2026;SP-9(9):598-607. doi: <https://www.doi.org/10.33545/2618060X.2026.v9.i9Sg.6730>