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Foam mat drying of perishable products: a critical review of process parameters, product quality, and sustainable prospects

Swanand Kalambe *[ab] and Sadanand Guhe[a]

Foam mat drying (FMD) is emerging as a cost-effective and energy-efficient technology for preserving heat-sensitive perishable products such as fruits, vegetables, dairy formulations, and protein-rich matrices. By incorporating air into liquid or semi-solid substrates, foam mat drying enhances surface area, accelerates drying kinetics, and improves retention of nutritional, structural, and sensory attributes. While previous reviews have discussed foam mat drying in general terms, a focused, parameter-specific evaluation across diverse food categories remains limited. This review provides an in-depth analysis of critical process parameters, such as foaming agent type and concentration, whipping time, foam thickness, drying temperature, and air velocity, and their effects on product quality indicators, including nutrient retention, rehydration ability, color stability, and shelf-life. The inclusion of comparative data tables, impact matrices, and decision-support tools offers actionable insights for optimizing drying protocols. Notably, this review integrates advanced modeling techniques, including response surface methodology (RSM), artificial neural networks (ANNs), and machine learning algorithms to predict drying behavior and maximize process efficiency. Sustainability considerations such as energy consumption, environmental impact, and the use of bio-based foaming agents are also critically examined. This review bridges scientific research and industrial practice, serving as a comprehensive resource for food scientists, technologists, and stakeholders in sustainable food processing.

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Sustainability spotlight

This review critically evaluates foam mat drying (FMD) as a sustainable technology for preserving perishable, heat-sensitive food products. By addressing process parameters, energy efficiency, and product quality, the work highlights FMD's environmental and industrial advantages over conventional drying techniques. It uniquely integrates modeling tools such as RSM, ANNs, and machine learning to advance process optimization and sustainability. With applications across underutilized food matrices including dairy and probiotics, this study supports more responsible food preservation practices. The review aligns with UN Sustainable Development Goals 9 (Industry, Innovation and Infrastructure) and 12 (Responsible Consumption and Production), contributing to resilient food systems and sustainable processing strategies.

1. Introduction

Drying is one of the ancient, easiest, and widely used preservation techniques in the food, nutraceutical, and pharmaceutical industries.[1] The presence of moisture in a substance or product may lead to microbial growth and activation of enzymatic activity, causing degradation of the substance.[2] Perishable food products like fruits, vegetables, dairy products, seafood, and certain plant extracts are highly valued for their rich nutritional profiles, including essential vitamins, minerals, antioxidants, and phytochemicals. However, these products are inherently unstable due to their high moisture content and biological activity, making them prone to rapid microbial spoilage, enzymatic browning, oxidation, and textural degradation. Without proper preservation, these changes can occur within hours to days after harvest or processing, leading to significant losses in both quantity and quality. Globally, food spoilage contributes to over one-third of all food waste, a concern that is not just economic, but also environmental and ethical.[3] In developing countries, where cold chain infrastructure is often inadequate or unavailable, preservation techniques become critical for ensuring food availability, reducing post-harvest losses, and promoting value addition.[4] Moreover, the growing consumer demand for nutritionally intact, safe, and shelf-stable products necessitates the development of gentle yet effective drying and preservation techniques.

[a]*Jawaharlal Nehru Engineering College (JNEC), MGM University, Chhatrapati Sambhajinagar, Maharashtra, India. E-mail: kalambeswanand@gmail.com; Tel: +919370291114*

[b]*Mahatma Gandhi Institute for Rural Industrialization (MGIRI), Wardha, Maharashtra, India*

Table 1 Comprehensive table of foam mat drying studies (2000–2025)

Sr. no.	Food type (study)	Key process parameters reported	Main findings/outcomes	Source (author and year)
1	Mango pulp	Foaming agents (egg albumin and glycerol monostearate), whipping time, and drying temperature (50–70 °C)	Egg albumin (15%) produced the most stable foam. Drying time was reduced by over 50% compared to pulp drying. Optimal quality was found at 60 °C	Kudra T. & Ratti C. (2006)[8]
2	Tomato pulp	Foaming agents (egg albumen and methyl cellulose), foam density, and drying temperature (60–80 °C)	A stable foam was achieved with 5% egg albumen. Foam mat drying at 70 °C produced high-quality tomato powder with good reconstitution properties and lycopene retention	Kadam D. M. *et al.* (2012)[22]
3	Banana pulp	Egg albumin concentration (0–16%), maltodextrin concentration (0–10%), and drying temperature (50–70 °C)	8% Egg albumin and 10% maltodextrin were optimal. Drying temperature significantly affected acidity and vitamin C retention; 60 °C was optimal	Thuwapanichayanan R. *et al.* (2008)[23]
4	Guanábana (soursop) pulp	Foam thickness (2, 3, and 5 mm) and drying air temperature (50, 60, and 70 °C)	Drying time increased with foam thickness. The Page model best described the drying kinetics. A temperature of 70 °C and a 2 mm thickness were the most efficient	Baptestini F. M. *et al.* (2018)[24]
5	Bambara groundnut (*Vigna subterranea*) yogurt	Gum arabic (6%) and methylcellulose (0.5%) (foaming agents), foam thickness, and drying temperature (50–70 °C)	Successfully produced a Bambara groundnut yogurt. Effective for creating a novel dairy product	Hardy Z. *et al.* (2020)[25]
6	Blueberry juice	Foaming agents (2.8 of maltodextrin/whey protein isolate (M3W1), trehalose/β-lactoglobulin (T3BL1), and trehalose/bovine serum albumin (T3A1)), stabilizer (gum arabic), and drying temperature	Maltodextrin/whey protein isolate (M3W1) was the most effective foaming agent. The process effectively preserved anthocyanins and antioxidants, producing a high-value functional powder	Darniadi S. *et al.*, (2017)[26]
7	Raspberry pulp	Maltodextrin addition, foam mat thickness, and microwave-assisted drying power levels	Microwave-assisted foam mat drying drastically reduced drying time (to minutes instead of hours). The product retained good color and high antioxidant activity	Lang S. *et al.*, 2020 (ref. 27)
8	Spirulina biomass	Foaming agent glair/egg albumen (popular as white egg) at 2.5% by weight at an air velocity of 2.2 m s^{-1}	Foam mat drying was a viable, low-cost method for drying *Spirulina*. It preserved high protein content and phytochemicals better than solar drying	A. Prasetyaningrum *et al.*, 2012 (ref. 28)
9	Coffee extract	Foaming agents, whey protein and maltodextrin	Produced instant coffee powder with improved solubility and aroma retention compared to spray drying. The process was found to be less energy-intensive for high-value extracts	Maciel K. S., *et al.*, 2023 (ref. 29)
10	Pomegranate juice	Whey protein isolate (WPI; 0%, 5%, 7.5% and 10%) and carboxymethyl cellulose (CMC; 0%, 0.25%, 0.5% and 0.75%) as foaming agents, different drying temperatures (50, 60 and 70 °C) and thickness (3 and 6 mm)	A drying temperature of 60 °C and a foam thickness of 3 mm were found to be acceptable drying conditions. The retention of phenols, anthocyanins, ascorbic acid, and antioxidant capacity was 97.86%, 83.90%, 77.29%, and 87.11%, respectively	Gaikwad N. N. *et al.*, 2024 (ref. 30)

Table 1 (Contd.)

Sr. no.	Food type (study)	Key process parameters reported	Main findings/outcomes	Source (author and year)
11	Coconut milk	Sodium caseinate (4% w/v) and maltodextrin (17.5% w/v) as foaming agents	The production methodology was upscaled to confirm the recovery of powder, which was 33.0 ± 0.7% (w/v). Cost economics revealed that the venture is profitable (BCR: 1.13) with an internal rate of return (IRR) of 33% and a break-even period of 206 days	Shameena Beegum P. P., *et al.*, 2022 (ref. 31)
12	Acerola pulp	Foaming agents (soy protein and egg albumin) and drying air temperature (50–80 °C)	Foam mat drying at 60 °C best preserved vitamin C (ascorbic acid), which is highly heat-sensitive. The powder exhibited high antioxidant capacity	Silva I. D. L. *et al.* (2018)[32]
13	Banana pulp	Soya protein and hen's egg albumin were used as foaming agents	For drying of banana pulp, it was found that egg albumen was better than soy isolate	Ali L. *et al.* (2020)[33]
14	Sea buckthorn juice	The conversion of seabuckthorn juice/pulp into foam was standardized by whipping the pulp after the addition of CMC at 0–3% at 5 °C and drying the resultant foam in a dehydrator (55 ± 2 °C) to a moisture content of about 12–14%	The method for the preparation of seabuckthorn leather using sulphited pulp (600 ppm SO_2) by converting it into foam, followed by drying and packing in PE pouches, was found to be the most appropriate for utilization of vitamin C, carotene, polyphenols and protein enriched seabuckthorn berries	Kaushal M. *et al.* (2011)[34]

Today, foam mat drying (FMD) has been extensively studied in academic research due to its superior nutrient retention, energy efficiency, and applicability to heat-sensitive materials like fruits, vegetables, dairy, and probiotics.[5] However, its industrial or commercial adoption remains in early stages of development. Academic work on yogurt powders, for example, has validated the feasibility of FMD for preserving probiotic viability and nutritional quality under controlled drying conditions, while pilot-scale continuous foam mat dryers have been engineered for tomato and guava, highlighting the technology's industrial potential.[6,7] On the industrial front, early commercialization attempts date back to Campbell's patented process for foamed evaporated milk (US 1250427A), and more recent patents have focused on foamed fruit juice powders, protein-enriched snacks, and probiotic encapsulation systems (*e.g.*, US4104414A, 1974; WO2015010748A1, 2013; US20120263826A1, 2012).[8–11] However, unlike spray drying and freeze drying, clear evidence of large-scale commercial foam mat drying products is limited, with most examples reported at the laboratory or pilot scale.[12] This dual trajectory – rapid academic growth alongside gradual industrial exploration – emphasizes that foam mat drying is poised for broader translation into industry, contingent upon advances in equipment design, continuous processing, and validation of economic feasibility.

Preserving perishable products extends their usability, allows seasonal products to be available year-round, and supports the formulation of ready-to-use powders and ingredients in functional foods, nutraceuticals, and reconstitutable beverages. Thus, selecting a preservation method that not only ensures microbial and physicochemical stability but also retains the nutritional and sensory integrity of the product is of paramount importance in today's food industry. The drying process offers the inhibition of microbial growth and enzyme activity and extends the shelf life of a product.[13] Today, several drying technologies like spray drying, freeze drying, and drum drying are used in food and pharmaceutical industries for drying of products. However, each method is characterized by distinct advantages and limitations in terms of product quality, energy consumption, and cost effectiveness. Among these techniques, foam mat drying (FMD) has emerged as a promising, cost-effective technology, especially for heat-sensitive liquid and semisolid products.[14]

The foam mat drying technique involves the conversion of a liquid or semisolid material into stable foam with the help of foaming agents and stabilizers, followed by drying the foam as a thin layer with the help of convective hot air at temperatures ranging between 50 °C and 70 °C.[15] Foam formation causes increased surface area and porous structures, leading to rapid moisture removal, reduced drying time, and lowered energy consumption.[16] Unlike the freeze-drying method, which is highly energy-consuming and expensive, or spray drying, which is unsuitable for viscous and fibrous materials, the foam mat drying method offers an efficient and cost-effective alternative that also preserves the nutritional, sensory, and functional quality of the final dried product.[15] The form mat drying method has several advantages, like retention of heat-sensitive bioactive compounds such as vitamins, antioxidants, pigments, and proteins; improved rehydration characteristics; and better preservation of aroma and flavor of compounds.[17] These advantages make this technique suitable for a wide range of applications. In the food industry, FMD is implemented for drying of fruit juices, pulps, dairy products, and egg-based substances, whereas in the pharmaceutical and nutraceutical industries, FMD is applied to process plant extracts, enzymes, probiotics, and other bioactive compounds that need gentle handling during drying.[18] In recent years, the integration of FMD with hybrid drying technologies such as microwave-assisted or infrared-assisted drying has further enhanced drying efficiency and product quality.[19] Moreover, computational modeling and predictive tools, including machine learning and response surface methodology, are increasingly used to optimize process parameters for diverse food matrices.[20]

Despite the several advantages offered by foam mat drying (FMD), its efficiency and the quality of the final dried product are highly dependent on a range of critical process parameters like foam density, mat thickness, drying temperature, air velocity, and whipping conditions.[15] These variables collectively affect key drying kinetics like moisture diffusivity and drying rate and vital product attributes such as nutrient retention, color, texture, solubility, and rehydration capacity. If not properly optimized, these factors can compromise both process performance and product quality, limiting the broader applicability of FMD in industrial settings.[21] The objective of the present review is to deliver a systematic and critical evaluation of how these process parameters affect foam mat drying outcomes. This review considered peer-reviewed experimental studies published in English between 2000 and 2025, excluding non-English papers, editorials, and non-food applications, which are summarized in Table 1. Each parameter is examined in detail, with a focus on its mechanistic influence on heat and mass transfer, structural transformation during drying, and the preservation of bioactive compounds. Additionally, the review highlights the importance of process integration and optimization strategies, including statistical modeling and machine learning approaches, to achieve a balanced trade-off between drying efficiency, product functionality, and energy use. Beyond technical aspects, this review underscores the growing relevance of sustainability considerations, such as minimizing energy consumption, reducing the environmental footprint, and employing bio-based, food-grade foaming agents. Altogether, this review aims to bridge scientific research with industrial relevance, offering practical insights for researchers, technologists, and stakeholders committed to sustainable food preservation solutions.

2. Evolution and historical development of foam mat drying

The origins of foam mat drying (FMD) trace back to the early 20th century, with foundational contributions from the food industry aiming to improve the shelf life and stability of liquid food products. The earliest known commercial application of FMD was developed in 1917 by the Campbell Soup Company, which devised a method for drying foamed evaporated milk, thereby setting a precedent for foam-based dehydration techniques.[35] This marked a pivotal moment in food processing, introducing the concept of transforming a liquid food matrix into a stable foam that could be rapidly and uniformly dried. Subsequent innovations were spearheaded by Morgan and colleagues, who filed a series of patents in the mid-20th century for drying foamed egg whites, an advancement that not only validated the commercial potential of FMD but also demonstrated its applicability to proteinaceous, highly perishable substrates.[36] These early applications laid the groundwork for adapting foam-based drying to a wider range of foods, with improvements in foam formulation, stabilization, and thermal processing techniques emerging over time.

Although its commercial uptake was initially limited to niche applications, foam mat drying has experienced a significant resurgence in research and development over the past two decades, particularly in response to growing demand for nutrient-preserving, energy-efficient, and scalable drying methods. Recent literature documents the successful application of FMD to a broad array of fruit and vegetable matrices, including apples, beetroot, bitter gourd, blueberry juice, dates, guava, potatoes, pumpkin, sour cherries, tomatoes, bananas, yacon, and yams.[37,38] These studies have demonstrated FMD's capability to retain natural color, flavor, and heat-sensitive nutrients that are typically degraded in conventional drying techniques.[38]

Briefly, foam mat drying is a two-stage process involving the generation of a stable foam from liquid or semi-liquid food materials, such as fruit juices, vegetable purees, dairy emulsions, or cereal pastes, followed by drying of this foam in thin layers under controlled convective or radiative heat (as shown in Fig. 1). In the foaming stage, the food substrate is vigorously whipped using mechanical mixers or homogenizers in the presence of food-grade foaming agents (*e.g.*, egg albumin, soy protein isolate, and methylcellulose), stabilizers (*e.g.*, gum arabic and maltodextrin), and sometimes texturizers or emulsifiers.[38] The objective is to incorporate air into the matrix, producing foam characterized by uniform bubble distribution, sufficient mechanical strength, and thermal stability.[39] The resulting foam is then spread into thin layers (typically 2–5 mm) onto drying trays or belts and subjected to moderate temperature airflow, typically between 50 °C and 70 °C.[40] Unlike conventional drying systems that dehydrate dense, unstructured solids, foam mat drying capitalizes on the high surface area and porous nature of foams to accelerate moisture removal, often reducing drying times substantially.[8] The final dried product, which assumes a brittle, honeycomb-like structure, can be easily pulverized into a fine, free-flowing powder with excellent rehydration characteristics.[8,9] Importantly, foam mat drying represents a fundamentally different approach compared to traditional drying technologies such as freeze drying, spray drying, or hot air drying. While conventional methods typically affect the food's microstructure post-dehydration, foam mat drying involves structural modification during the drying process itself. The incorporation of air leads to partial disruption of cell walls and reorganization of

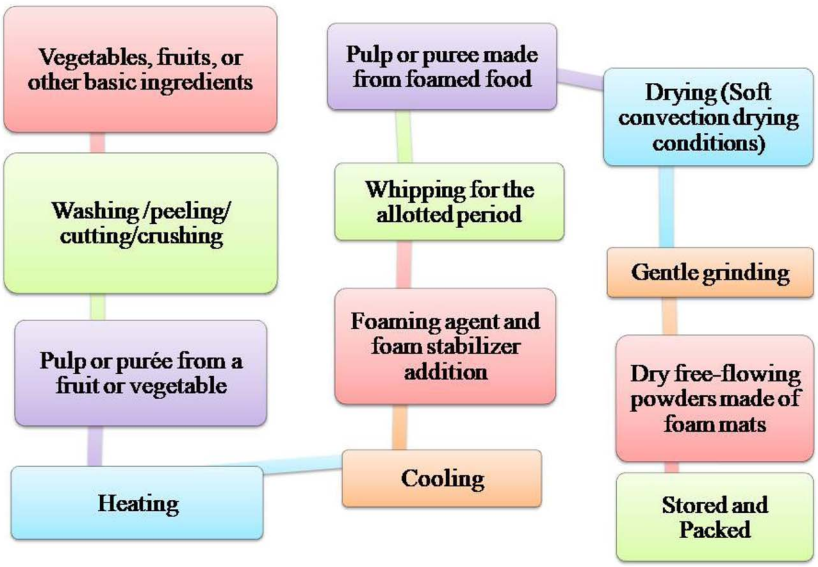

Fig. 1 Steps involved in the Foam Drying Process (FMD).

intracellular components, resulting in a dried matrix with enhanced porosity, dispersibility, and rehydration capacity.[8,9] Moreover, modern adaptations of foam mat drying incorporate hybrid drying systems, integrating infrared or microwave energy to further improve drying efficiency and preserve thermolabile compounds.[20,41] This flexibility has positioned foam mat drying as a viable and versatile solution for preserving perishable food products, particularly those rich in bioactive compounds and sensitive to oxidative or thermal degradation.

Thus, the evolution of foam mat drying from an early 20th-century innovation to a contemporary food preservation technology reflects not only advances in food engineering and process optimization but also the growing prioritization of quality retention, energy sustainability, and product functionality in modern food systems.

3. Process parameters and their effects in foam mat drying

The efficiency of the foam drying process and the quality of the final powder are intricately governed by several critical process parameters. These include drying temperature, foam thickness, foam density, air velocity, and foaming agent characteristics, all of which directly affect the mass and heat transfer dynamics and the physicochemical and nutritional properties of the end product.[42] An in-depth understanding and precise control of these parameters are essential to achieving product-specific goals such as high nutrient retention, desirable texture, rapid drying, and minimal energy input (Table 2).

3.1. Drying temperature

One of the most influential parameters is drying temperature, which significantly affects both drying kinetics and the thermal stability of food components. Higher drying temperatures accelerate the rate of water evaporation due to increased vapor pressure gradients, thus shortening the overall drying time. However, the use of elevated temperatures can result in substantial degradation of heat-sensitive nutrients and phytochemicals, including vitamin C, polyphenols, and carotenoids. For example, Kandasamy *et al.* (2012) demonstrated that foam mat drying of papaya pulp at 60 °C achieved a favorable balance between drying efficiency and nutrient preservation, retaining approximately 88% of the original vitamin C content, whereas drying at 80 °C reduced retention below 65% (Table 3).[43]

3.2. Foam thickness

Another key factor influencing FMD performance is foam thickness, which affects the internal diffusion path length and thus the uniformity of moisture removal. Thin foam mats (generally in the range of 2–5 mm) enable faster drying and more consistent heat transfer throughout the matrix.[44] In

Table 2 Optimal ranges for foam mat drying parameters

Parameter	Optimal range	Food category	Reference
Drying	50–70 °C	Fruits, vegetables, and dairy	Kandasamy *et al.*, 2012;[43] Kumar *et al.*, 2022 (ref. 52)
Foam thickness	2–5 mm	Fruit pulps and dairy emulsions	Mohan *et al.*, 2018 (ref. 53)
Air velocity	1.5–2.5 m s^{-1}	Fruit pulps and root crops	Ndukwu, 2009;[54] Gazor and Minaei, 2005 (ref. 55)
Foaming agent concentration	5–10% (proteins)	Papaya, tomato, and mango	Belal *et al.*, 2020;[56] Hossain *et al.*, 2024 (ref. 57)

Table 3 Summary table of product quality attributes influenced by foam mat drying

Quality attribute	Affected by	Scientific insight	Ref.
Nutrient retention	Drying temp, foam density, and thickness	Up to 90% vitamin C retention at 60 °C	58
Color stability	Temperature, air velocity, and foam stability	β-Carotene retention up to 90% at 60 °C	37
Flavor preservation	Drying time and air velocity	Better aroma retention *vs.* spray drying	59
Textural integrity	Foam thickness and whipping time	Uniform porosity prevents shrinkage and collapse	23
Flowability & dispersibility	Foam structure and drying temperature	Instant dispersibility in <20 s (Sharma *et al.*, 2013)	60
Rehydration	Porosity, surface area, and drying uniformity	High rehydration ratio was observed in mango powder (Kandasamy *et al.*, 2014)	43

contrast, thicker layers (>6 mm) often experience non-uniform drying, with the outer layers forming a hardened crust that impedes internal moisture escape, a phenomenon known as case hardening.[45] This not only prolongs drying time but also compromises product rehydration and textural integrity.

3.3. Foam density

Closely related to foam thickness is foam density, which governs porosity, surface area, and structural stability. Low-density foams, characterized by high air incorporation (typically 0.3–0.5 g cm^{-3}), tend to dry faster due to their increased surface area and lower thermal mass.[46] However, if the foam is too light or unstable, it may collapse during drying, leading to compacted powders with poor solubility and dispersibility.[46] The type and concentration of the foaming agent play a pivotal role here. Verma *et al.* (2019) demonstrated that a 10% concentration of egg albumin generated stable foam with suitable density and drying characteristics for papaya pulp.[47] Moreover, the adoption of sustainable, plant-derived foaming agents, such as soy protein isolate and saponins, offers a promising alternative to traditional animal-derived options.[48]

3.4. Air velocity

Air velocity is another important parameter, as it regulates the convective transfer of heat and mass across the foam mat surface. Increased air velocity reduces the boundary layer thickness, thereby enhancing surface moisture removal during the early stages of drying. However, excessive airflow can result in physical deformation or "blow-off" of fragile foams, particularly those with low density or inadequate structural cohesion. Empirical studies indicate that an air velocity in the range of 1.5 to 2.5 m s^{-1} is optimal for most fruit pulps, ensuring efficient moisture transfer while maintaining foam integrity.[49]

3.5. Whipping time

The properties of the foam itself are determined in large part by whipping time and foaming agent concentration, which together influence bubble size distribution, foam expansion, and rheological behavior. A whipping time that is too short results in insufficient air incorporation and poor foamability, whereas over-whipping can lead to foam collapse due to bubble coalescence or excessive viscosity.[49] Meena A *et al.* (2024) found that whipping papaya pulp for 10 minutes with a 10% egg albumin concentration yielded uniform and stable foam, which dried efficiently and produced a powder with excellent rehydration characteristics.[50] Additionally, the molecular interactions between foaming agents and food matrix components (*e.g.*, proteins and polysaccharides) can impact foam stabilization mechanisms, especially under heat stress during drying.[51]

Importantly, these parameters do not act independently but exhibit complex interdependencies. For example, the ideal foam thickness may vary with drying temperature and air velocity while foam density and whipping time interact to influence both drying kinetics and final product texture.[46] Thus, optimizing foam mat drying requires a holistic, multivariate approach. Techniques such as response surface methodology (RSM), artificial neural networks (ANNs), and principal component analysis (PCA) have been successfully employed to model these interactions and determine optimal conditions that balance drying time, energy efficiency and quality attributes.

4. Drying kinetic models in foam mat drying

Foam mat drying (FMD) is a novel drying method that involves creating a foam layer and slowly drying food items to extract moisture. The drying behavior of the FMD processes can be described using several drying kinetic models. The following are some popular models:

4.1. Thin layer drying models

Page model: the thin-layer drying dynamics are commonly described by the Page model.[61] The drying rate was assumed to be proportional to the difference between the moisture content of the material and its equilibrium moisture content. The formula is as follows:

$$M/M_0 = (1 - kt)^n$$

where D = drying rate constant, n = Page constant, M = moisture content at time t, and M_0 = initial moisture content.

4.2. Diffusion-based models

Fick's diffusion model: this model, which is predicated on Fick's second law of diffusion, holds that the moisture gradient and drying rate of the material are directly correlated.[62] The formula is as follows:

$$dM/dt = D \times \partial^2 M/\partial x^2$$

where M = moisture content, t = time, D = effective diffusion coefficient, and x = distance within the material.

4.3. Empirical models

Midilli–Kucuk model: the Midilli–Kucuk model is an empirical model that combines aspects of both diffusion and mass transfer phenomena.[63] It is expressed as

$$dM/dt = k(M - M_e)^{\beta}$$

where k and β = empirical constants and M_e = equilibrium moisture content.

4.4. Semi-empirical models

Modified Page model: this model is a modification of the Page model and incorporates both empirical and theoretical aspects.[63] It is given as

$$dM/dt = -k(M - M_e)^{n+k'/M}$$

where k, n, and M_e retain their previously defined meanings, while k' is an additional empirical constant incorporated to improve the model's fit to experimental data.

5. Foaming agents and their functional roles in foam mat drying

In the foam mat drying (FMD) process, the use of foaming agents is crucial for forming stable, uniform foams that facilitate rapid drying while preserving product quality. Foaming agents, typically surfactants or proteins, lower the surface tension at air–liquid interfaces, enabling the formation of stable foams. These agents rapidly adsorb at the interface, forming viscoelastic films that resist coalescence and collapse under thermal and mechanical stress. The choice of foaming agent profoundly affects foam expansion, density, drying kinetics, and the physicochemical properties of the final product.

5.1. Protein-based foaming agents

5.1.1 Egg albumen (egg white). Egg albumen is widely recognized as a highly effective natural foaming agent due to its excellent whipping ability and interfacial film-forming properties. Upon whipping, the albumen proteins denature and interact at the air–water interface, forming a continuous, cohesive, and elastic matrix that stabilizes the foam structure.[64] Md. Belal *et al.* (2022) studied tomato juice using different concentrations of egg albumin (3%, 5%, and 7%) in combination with carboxymethyl cellulose (CMC).[64] The optimal formulation, 7% egg albumin with 1% CMC, resulted in highly stable foams with superior density and expansion properties. Similarly, Hossain *et al.* found that this combination preserved both physical and nutritional quality of tomato powder when dried at 60 °C, underscoring the role of egg albumen in maintaining bioactivity under moderate thermal stress.[65]

5.1.2 Whey protein. Whey protein concentrate (WPC), a byproduct of cheese production, is another highly functional foaming agent due to its amphiphilic nature and slow unfolding kinetics. Thuwapanichayanan *et al.* (2012) studied the foamability and drying performance of banana puree using WPC, egg albumen, and soy protein isolate (SPI).[37] WPC-based foams demonstrated superior stability and moisture diffusivity, attributed to their open structure and minimal shrinkage. Although WPC required a longer whipping time (50 minutes) compared to egg albumen (20 minutes), the resulting foam was more resilient and porous, favoring efficient drying.[65] Furthermore, Abirached *et al.* (2012) compared the interfacial behavior of WPC and SPI, showing that WPC forms foams with greater stability and lower drainage rates.[66] Surface rheology data revealed that WPC had a significantly higher dilatational modulus ($p < 0.05$), suggesting enhanced resistance against film rupture and disproportionate[66]

5.1.3 Soy protein isolate (SPI). SPI, with over 90% protein content, is derived from defatted soybean meal and exhibits strong foaming potential due to its surface activity and structural flexibility.[67] According to Asokapandian S *et al.* (2016), the optimum conditions for foam formation using SPI involved 8.71% SPI, 0.54% CMC, and 5.7 minutes of whipping. These conditions produced foams with adequate stability and uniformity suitable for drying.[68] In another study (Eman Farid *et al.*, 2022) it was reported that 5% SPI with 8 minutes of whipping yielded tomato powder with significantly improved phytochemical retention: total phenolics increased by 97%, flavonoids by 39%, antioxidant activity by 62%, and porosity by 46%, while bulk density decreased by 25%. These findings underscore SPI's ability to maintain functional properties and the structure during thermal drying.[69]

5.1.4 Guar foaming albumin (GFA). Guar foaming albumin, a plant-based protein extracted from guar meal, exhibits exceptional foaming capacity, reportedly ten times higher than that of egg albumen at low concentrations. GFA forms small, uniform bubbles that confer high rigidity and stability to the foam. In the study by Shimoyama *et al.* (2008), GFA significantly reduced water surface tension and demonstrated a 20-fold increase in foaming activity compared to egg white. Importantly, immunoblotting assays showed no reactivity with plant food allergen antisera, suggesting GFA as a hypoallergenic alternative to animal-derived foaming agents.[70]

5.2. Foam stabilizers: polysaccharides and their synergistic role

Foam stability is further enhanced by the inclusion of stabilizers, primarily polysaccharides, which increase the viscosity of the liquid phase and restrict bubble coalescence. Common stabilizers include carboxymethyl cellulose (CMC), xanthan gum, pectin, starch, gelatin, and gum arabic. CMC in particular is frequently used alongside protein-based foaming agents to enhance foam consistency and durability. The synergistic effect of CMC with proteins such as egg albumen and SPI has been well documented. As demonstrated in studies by Belal *et al.* (2022) and Hossain *et al.* (2021), the incorporation of 1% CMC significantly improved foam expansion and density, while also minimizing structural collapse during drying.[64,65]

The mechanism of stabilization involves the creation of a semi-solid network within the liquid film, which resists gravitational drainage and gas diffusion. According to Zhou *et al.* (2020), this network formation slows down foam aging processes, including coalescence, Ostwald ripening, and film rupture, thereby prolonging foam life under thermal stress.[6]

6. Advanced modeling and optimization techniques in foam mat drying

The complexity and multivariable nature of the foam mat drying (FMD) process make it an ideal candidate for advanced modeling and optimization approaches. Traditional empirical methods, while useful, often fall short in accurately predicting process behavior across a wide range of operating conditions. Recent advancements in computational modeling, artificial intelligence (AI), and machine learning (ML) have opened new frontiers in optimizing foam mat drying, enabling precise control over process parameters to maximize product quality, minimize energy consumption, and improve reproducibility, as shown in Fig. 2.

6.1. Computational modeling and response surface methodology (RSM)

Response Surface Methodology (RSM) has been widely employed to study the interactive effects of critical process variables such as drying temperature, foam thickness, whipping time, and air velocity. This statistical tool facilitates the development of predictive models and optimization of process conditions with minimal experimental trials. For example, optimization by RSM, using 4% egg albumin and 10–15 minutes of whipping, yielded plum powder with superior dehydration efficiency, structural integrity, and antioxidant retention. The study demonstrated that both foaming agent concentration and whipping duration critically influence physicochemical and bioactive properties in foam mat drying, supporting process-specific tailoring for quality preservation.[71] Similarly, Isa *et al.* (2019) optimized the drying process of watermelon pulp drying using RSM. The study revealed that inlet temperature, air velocity, CMC, and egg albumin have a significant influence on the drying process.[72] In a study by Hossain *et al.* (2024), optimization through RSM revealed that 4.59% egg albumin, 0.70% CMC, and 60 °C drying temperature produced tomato powder with desirable physicochemical properties, including high foam expansion (346.60%) and excellent nutrient retention (2.93 mg/100 mL ascorbic acid).[17] The high predictive accuracy ($R^2 > 85\%$, RSE $\leq$ 5) confirmed the robustness of the model, demonstrating foam-mat drying as a reliable technique for producing high-quality tomato powder with controlled process variables.[73] RSM not only enabled them to identify optimal drying conditions (65 °C, 4 mm thickness, 2 m s^{-1} air velocity) but also helped visualize response surfaces that illustrate the tradeoffs between drying efficiency and nutrient preservation[74]

6.1.1 Artificial neural networks (ANNs). While RSM is based on quadratic relationships and may struggle with highly non-linear systems, Artificial Neural Networks (ANNs) offer a flexible option that can model complex, nonlinear interactions between multiple inputs and outputs. ANNs mimic the learning mechanisms of the human brain, allowing them to self-adapt and improve performance with increasing data. Thuy *et al.* (2024) implemented an ANN model to predict moisture content and drying rate in foam mat drying of lucuma powder.[46] The study found that drying temperatures have a significant impact on the quality of lucuma powder. ANNs have also been

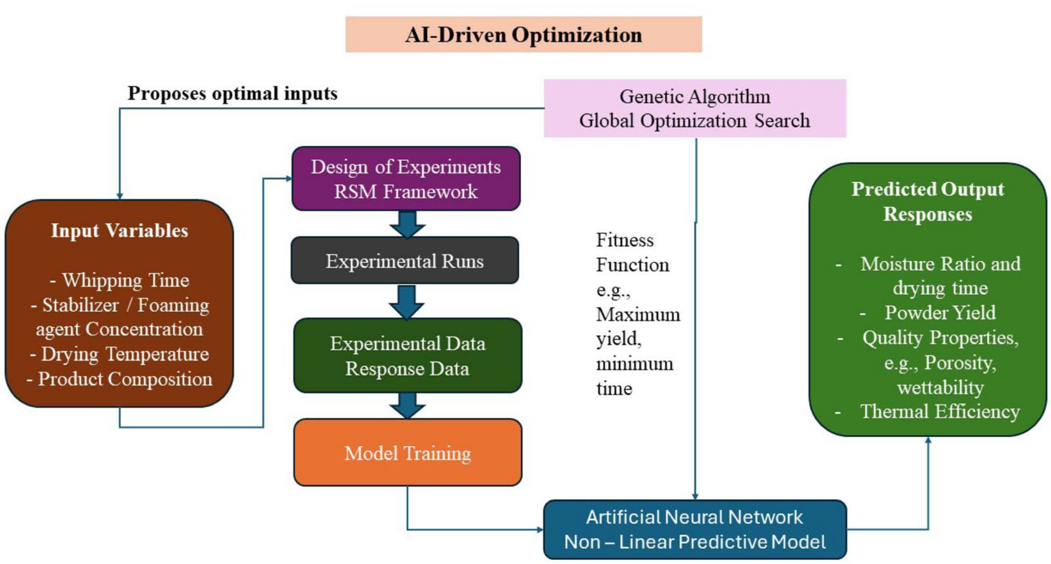

Fig. 2 Conceptual framework illustrating the integrated application of RSM, ANNs, and GAs for modeling and optimizing the foam mat drying process. LLMs are utilized as an auxiliary tool for computational and analytical tasks.

successfully used to model and predict quality attributes such as the rehydration ratio, color change, and nutrient loss. For example, Ghosh D *et al.*, 2020, applied ANNs to optimize drying parameters for FMD of tomato puree.[75] Their findings showed that ANNs could predict lycopene retention and color values with high precision, aiding in the development of process regimes that maintain both sensory and nutritional quality.[75]

6.1.2 Genetic algorithms (GAs) and hybrid AI techniques. Optimization using Genetic Algorithms (GAs) and other evolutionary computation methods has further enhanced the precision of drying system control.[76] GAs simulate natural selection by iteratively evolving a population of solutions, selecting the best-fit individuals, and generating new solutions *via* crossover and mutation.[77] When combined with ANNs (GA–ANN hybrid models), these methods can optimize multi-objective problems such as minimizing drying time while maximizing nutrient retention with high efficiency.[78] For example, Kudra and Mujumdar *et al.* (2009) proposed a GA-based optimization framework for convective drying processes and suggested its applicability to FMD systems.[79] Such hybrid models are increasingly being used in high-value food drying, where a balance between energy efficiency, product quality, and economic feasibility must be achieved.

6.1.3 Machine learning and big data integration. Emerging studies are now integrating machine learning (ML) algorithms, including support vector machines (SVMs), decision trees, and random forests, to extract patterns from large experimental datasets and predict outcomes under new or unseen conditions.[80] These data-driven models allow researchers to bypass complex physical modeling, relying instead on robust datasets to infer underlying process behavior. A novel application is the use of real-time sensor data, such as infrared thermography and humidity sensors, combined with ML models to dynamically adjust process parameters during FMD. Priyadarshini I *et al.* (2022) demonstrated a prototype system that combined ML-driven control with real-time moisture sensing, which significantly reduced energy consumption and improved final product consistency.[81]

6.1.4 Digital twins and predictive simulations. Looking forward, the development of digital twins, virtual replicas of physical drying systems, represents the next leap in FMD optimization. By coupling physics-based models with real-time process data and ML algorithms, digital twins can simulate multiple scenarios simultaneously, enabling pre-emptive fault detection, dynamic optimization, and adaptive control.[82]

7. Sustainability considerations in foam mat drying

Foam Mat Drying (FMD) has gained attention not only for its superior preservation of sensory and nutritional quality in heat-sensitive foods but also for its comparatively lower environmental footprint and energy efficiency. As global food systems are increasingly pressured to meet sustainability goals, evaluating the ecological implications of food preservation technologies is vital. FMD, when benchmarked against traditional drying techniques such as spray drying, freeze drying, and convective hot air drying, shows significant advantages in terms of reduced energy consumption, shorter processing times, and lower greenhouse gas emissions.

7.1. Energy consumption

The energy efficiency of FMD is one of its most compelling sustainability attributes. Unlike freeze drying, which requires sublimation under vacuum at extremely low temperatures and consumes between 20 and 100 MJ kg^{-1} of water removed, foam mat drying operates under moderate conditions[82] of temperatures (50–80 °C) and atmospheric pressure, significantly reducing energy demands. According to Izadi *et al.* (2020), foam mat drying uses 40–60% less energy than freeze drying for comparable products, such as fruit powders.[83,84] In contrast to spray drying, which demands high inlet air temperatures (up to 180 °C) and substantial atomization energy, foam mat drying allows slower, layer-wise drying that conserves thermal energy and reduces losses associated with fine particle escape or wall deposition.[85] Moreover, the foam structure enhances the surface area to volume ratio, facilitating faster heat and mass transfer.[86] This results in reduced drying time (by 30–50% in many cases) compared to conventional hot air drying. For example, Kumar *et al.* (2022) reported that mango pulp dried using FMD at 70 °C achieved target moisture levels in less than 3 hours, while convective drying required over 5 hours under similar conditions.[52]

7.1.1 Water usage and water footprints in FMD. While the energy demand and greenhouse gas emissions of drying technologies have been studied extensively, their water usage and water footprint remain less systematically addressed, particularly in the context of foam mat drying. Conventional drying processes such as spray drying and freeze drying typically involve significant upstream water inputs during cleaning, slurry preparation, and cooling operations, contributing indirectly to the overall water footprint of the process.[87] Foam mat drying, in contrast, generally requires lower pre-processing water inputs, since the slurry is aerated with foaming agents rather than extensively diluted or homogenized as in spray drying.[17] Moreover, the relatively shorter drying times and reduced thermal load in foam mat drying indirectly decrease water consumption in ancillary operations (*e.g.*, cooling towers and cleaning cycles).[17]

Recent sustainability assessments of drying technologies indicate that spray drying of fruit juices can require up to 3–5 L of water per kg of finished powder when both direct and indirect usage are included (Izadi *et al.*, 2020), while freeze drying can exceed this due to extended drying times and equipment sanitation needs.[83] By comparison, foam mat drying has been reported to reduce this footprint by 20–30%, primarily due to lower utility water requirements during operation (Kumar *et al.*, 2022).[52] However, it should be noted that the choice of foaming agent may influence the water footprint indirectly, as some protein isolates or hydrocolloids require substantial water resources during upstream production.[88]

Table 4 Life cycle assessment (LCA) comparison of drying methods

Drying method	Energy consumption (MJ kg^{-1} water removed)	GHG emissions (relative %)	Reference
Foam mat drying	10–20	Low (30–60% lower than that of freeze drying)	Izadi *et al.*, 2020;[83] Kumar *et al.*, 2022 (ref. 52)
Freeze drying	20–100	High	Izadi *et al.*, 2020 (ref. 83)
Spray drying	15–40	Moderate	Khatri *et al.*, 2024 (ref. 18)
Hot air drying	15–25	Moderate–high	Calín-Sánchez *et al.*, 2020 (ref. 84)

In alignment with SDG 12 (Responsible Consumption and Production), foam mat drying therefore offers a promising pathway for reducing both the direct water use during drying and the indirect water footprint associated with overall production.[89] Integrating water usage metrics alongside energy and emission profiles in future Life Cycle Assessments (LCAs) would provide a more holistic evaluation of foam mat drying's sustainability.[90] This is particularly relevant for scaling foam mat drying in water-stressed regions, where minimizing both energy and water footprints is critical for resilient and responsible food processing.

7.2. Environmental impact and the carbon footprint

When considering greenhouse gas emissions and resource usage, foam mat drying offers further advantages. Freeze drying has one of the highest carbon footprints among dehydration technologies due to its intensive electricity usage and refrigerant systems.[91] On the other hand, foam mat drying is highly adaptable to renewable energy sources (*e.g.*, solar-assisted hot air systems), further reducing its dependency on fossil fuels. Studies comparing Life Cycle Assessment (LCA) parameters have shown that the global warming potential (GWP) and cumulative energy demand (CED) of FMD are 30–60% lower than those of freeze drying and 15–25% lower than those of spray drying for equivalent moisture removal.[92] This makes FMD an ideal choice for environmentally conscious food processing industries, especially in developing countries where energy access and sustainability are tightly interlinked (Table 4).

7.3. Material sustainability: clean-label and biobased inputs

Another key sustainability consideration is the source and nature of the foaming agents used in FMD. Unlike spray drying, which often relies on synthetic emulsifiers or carriers like maltodextrin, FMD processes can be tailored using natural, biodegradable foaming agents such as egg albumen, soy protein isolate, guar foaming albumin, and whey protein.[16] These biomaterials not only enhance foam stability but also align with clean-label product development, reducing the chemical load on both consumers and the environment. Additionally, emerging interest in plant-based and allergen-free foaming agents like decyl glucoside, coco glucoside, MSK Ultrawhip, *Quillaja saponaria*, and cocamidopropyl betaine offers opportunities for circular bioeconomy integration, where by-products such as legume proteins or fiber-rich extracts serve dual purposes of nutrition and functionality.[93–95]

8. Applications across diverse perishable products

Foam mat drying (FMD) has emerged as an effective technology for preserving highly perishable, heat-sensitive food products by reducing moisture content while minimizing degradation of nutritional and organoleptic properties. Its success hinges on rapid moisture removal, low thermal load, and structural stability of the foam matrix. The following sections provide a comprehensive exploration of FMD applications across different food categories, supported by experimental studies and comparative analyses.

8.1. Fruits and fruit juices

Fruits are typically rich in polyphenols, vitamins (notably vitamin C), and carotenoids, which are prone to thermal and oxidative degradation. FMD has demonstrated significant retention of these bioactives due to its mild drying conditions and short residence time. Md. Belal *et al.* (2020) developed tomato powder using varying concentrations of egg albumin (3–7%) and CMC (0.5–1%), finding that 7% egg albumin with 1% CMC at 60 °C provided optimal foam stability and retention of lycopene, ascorbic acid, and color intensity.[64] Ghanbarzadeh *et al.* (2017) reported that FMD produced sour cherry powders with 90–95% retention of anthocyanins and 88% antioxidant capacity when compared to freeze-drying, but at significantly reduced energy cost and time.[96] Thuwapanichayanan *et al.* (2012) showed that banana foams prepared with whey protein concentrate (WPC) had the highest effective moisture diffusivity (1.8×10^{-8} m^2 s^{-1}), the least shrinkage, and superior rehydration, confirming the strong performance of protein-stabilized foam in heat-sensitive tropical fruits.[37]

8.2. Vegetables and root crops

Vegetables, especially those high in pigments like carotenoids (carrot and pumpkin) or betalains (beetroot), are susceptible to degradation at high drying temperatures. A study by Mocanu *et al.* (2020) compared foam-mat drying and tray drying of red beetroot puree and found that foam-mat drying preserved higher levels of betacyanin (2600 mg kg^{-1}) compared to tray drying (1100 mg kg^{-1}), indicating better pigment retention.[97] Additionally, foam-mat drying resulted in higher chroma values, suggesting improved color preservation.[98] For carrot drying, a study by Suman and Kumari (2002) reported that hot air cabinet drying retained about 58% of β-carotene in dehydrated carrot products, which was higher compared to sun drying (29%) and solar drying (48%).[99] These findings suggest that foam-mat drying can be more effective in preserving β-carotene and betanin in beetroot and carrot powders compared to conventional hot air-drying methods. In another study based on foam-mat drying of mango pulp, the effects of soy protein isolate concentration on drying kinetics and product quality were investigated.[100] The research found that increasing the concentration of soy protein isolate improved foam stability and drying efficiency, leading to better retention of nutritional qualities, including vitamin C. Specifically, the study reported vitamin C retention rates of approximately 61.0 ± 0.7% under optimal conditions.[101]

8.3. Dairy and proteinaceous products

Drying dairy-based matrices is challenging due to protein denaturation and fat oxidation.[102] Foam-mat drying (FMD) has emerged as an effective technique for processing dairy products and protein-rich substances, offering advantages in preserving nutritional quality and improving drying efficiency. In a study by de Paula *et al.* (2020), whey was subjected to FMD at different temperatures, with findings indicating that drying at 60 °C resulted in optimal moisture content and protein retention, without significant degradation of protein quality.[103] Similarly, Febrianto *et al.* (2012) performed the FMD of milk by using different concentrations of fillers like maltodextrin and gum arabic.[104] The study concluded that the addition of 15% maltodextrin yielded milk powder with desirable moisture content and protein levels, demonstrating the potential of FMD in producing high-quality dairy powders.[104] Furthermore, the application of FMD in processing proteinaceous substances has shown promising results. For example, incorporating egg albumin and whey protein isolate as foaming agents in the drying of carrot juice not only enhanced the retention of bioactive compounds but also improved the thermal stability and microstructure of the resulting powder.[105] These findings underscore the versatility of FMD in preserving the functional and nutritional components of protein-rich foods, making it

Table 5 Summary of the foaming mat drying method applied to different food materials

Material	Foaming agents	Time for whipping in min	Drying temperature, °C	Ref.
Apple	Egg albumen Methyl cellulose	—	20	112
Apple	Gelatin	3–9	60	74
Banana	Egg albumin	—	60–80	113
Blue honeysuckle berry	Glycerol monostearate Carboxymethyl cellulose	2	140–700 W	114
Blackcurrant	Glycerol monostearate Carboxymethyl cellulose	—	140–700 W	115
Cowpea	Egg albumin Glycerol monostearate	3–21	60	116
Egg white	Xanthan gum Glycol alginate Methyl cellulose	5	20	112
Mandarin	Egg albumin Carboxymethyl cellulose Milk	—	65–85	117
Mango	Egg albumin Methyl cellulose	—	60–75	118
Malabar tamarind	Methocel Methyl cellulose Egg albumin	30 12	70 50–70	119
Papaya	Egg albumin Methyl cellulose Glycerol monostearate	10–15	60–70	43
Plantain	Glycerol monostearate	3–18	60–80	121
Pineapple	Tricalcium phosphate Egg albumin Carboxymethyl cellulose	—	65–85	122
Starfruit (*Averrhoa carambola* L.) puree	Methocel	4	70–90	123
Seabuckthorn	Carboxymethyl cellulose	3	55	34
Shrimp	Xanthan gum	5 min	50–70	124
Tamarind	Ovalbumin Mesquite gum	—	50	125
Tomato	Egg albumin	5	65–70	22
Yogurt	Egg albumin Methyl cellulose	12	50–70	120

a valuable technique in the food processing industry. Overall, the integration of FMD in the processing of dairy and proteinaceous products offers a viable alternative to conventional drying methods, ensuring product quality while enhancing energy efficiency and cost-effectiveness.

8.4. Underutilized and indigenous crops

FMD offers opportunities for value addition and shelf-life extension of nutritionally dense but underutilized crops, which are often lost due to inadequate postharvest technology. Yacon is high in fructo-oligosaccharides (FOSs), known for prebiotic effects. Franco *et al.* (2015) investigated the physicochemical and microstructural properties of yacon juice powder produced by FMD.[106] The study found that FMD resulted in powders with desirable properties like low moisture content and good solubility, indicating its potential as an effective drying method for yacon juice.[106] Yam flour from FMD showed better color retention and dispensability, facilitating instant reconstitution. FMD processing of date paste retained over 92% total phenolic content and exhibited superior antioxidant activity compared to sun drying.[107]

8.5. Functional foods and nutraceuticals

FMD is well-suited for drying matrices with thermolabile bioactives and volatile oils, making it ideal for nutraceutical and functional food development. A study on foam-mat drying of germinated rice bean (*Vigna umbellata*) hydrolysate found that FMD at 60 °C preserved higher levels of phenolic compounds, including catechins, and maintained strong antioxidant activity compared to higher drying temperatures.[108] The research highlighted that gallic acid, catechol, and epicatechin were major phenolic compounds retained in the foam-mat dried samples. Additionally, a study on foam-mat drying of Tommy Atkins mango demonstrated that the technique effectively preserved phenolic compounds and antioxidant capacity, with optimal retention achieved at specific concentrations of foam stabilizers and drying temperatures.[109] For instance, Gallardo-Rivera *et al.* (2021) investigated the viability of *Lactobacilli* in foam-mat dried yogurt using different drying techniques.[110] The study found that foam-mat drying at lower temperatures preserved LAB viability better than conventional drying methods.[110] Specifically, the viability of LAB was maintained above 70% when dried at 50–55 °C using foam-mat drying, while hot-air drying resulted in significantly lower viability.[110] This suggests that foam-mat drying is a more suitable method for preserving the viability of probiotics in dairy products. This highlights the feasibility of foam mat drying as a drying and encapsulation system for probiotic delivery. Tanganurat *et al.* (2020) investigated the survival of *Pediococcus pentosaceus* ARG-MG12 encapsulated in sodium alginate beads with various plant extracts (onion, soybean, and lotus root) during foam-mat drying.[111] The study found that co-encapsulation with 3% soybean extract significantly enhanced probiotic survival, achieving 98.39% viability after drying at 70 °C, compared to 87.55% in uncoated samples. Additionally, the encapsulated probiotics demonstrated improved stability under simulated gastrointestinal conditions (Table 5).[111]

9. Practical guidelines for industry: decision-making tools and best practice recommendations

The industrial implementation of the foam mat drying process requires a rational, evidence-based approach. Integrating scientific understanding with engineering practice facilitates the establishment of practical guidelines to ensure efficiency, product integrity, and economic feasibility.

9.1. Raw material selection and pre-treatment

The selection of raw materials must be based on the physicochemical properties of the target product, including pH, sugar content, viscosity, and sensitivity to heat. Products with high sugar and acid content (*e.g.*, fruit juices) are ideal candidates due to their inherent foam-forming potential. Pre-treatments such as enzymatic clarification or pH adjustment can enhance foaming properties and improve drying kinetics.[73] In a study by Kadam *et al.* (2011), they examined the effects of different concentrations of egg albumin as a foaming agent and varying drying temperatures on the quality of foam-mat dried tomato juice.[117] The study highlighted the significance of optimizing processing parameters to enhance foam stability, drying efficiency, and the quality of the resulting tomato powder.

9.2. Optimization of foaming agents and stabilizers

For a consistent foam structure and drying performance, the concentration and type of foaming agent must be optimized. Proteins such as egg albumen, whey protein concentrate (WPC), and soy protein isolate (SPI) are commonly used due to their amphiphilic nature and interfacial viscoelasticity. Egg albumen (5–7%) with carboxymethyl cellulose (0.5–1%) has been found to produce highly stable foam with low shrinkage and excellent nutrient retention.[64,65] Response surface methodology (RSM) or desirability-based optimization can be helpful to determine the best combination of foaming agent, stabilizer, and whipping time for target metrics such as foam density, expansion, and stability.

9.3. Drying temperature and airflow conditions

Drying temperature must be carefully controlled to ensure rapid moisture removal without degrading heat-sensitive compounds. Most studies recommend a range between 50 and 70 °C, with air velocities between 1 and 2.5 m s^{-1} for optimal drying efficiency and quality retention. For example, Gazor and Minaei (2005) investigated the drying of pistachios at temperatures of 60, 75, and 90 °C with air velocities of 1.5, 2.0, and 2.5 m s^{-1}. They found that increasing the temperature to 90 °C reduced drying time by about 37% but adversely affected flavor.[55] An air velocity increase from 1.5 to 2.5 m s^{-1} reduced drying time by approximately 10%, with minimal impact on protein and fat content.[55] In another study, Ndukwu (2009) studied the drying of cocoa beans at temperatures of 55, 70, and 81 °C and air velocities of 1.3, 2.51, and 3.7 m s^{-1}. The study concluded that higher temperatures and air velocities improved drying rates, with the drying constant increasing alongside these parameters.[54] V. P. Chandramohan *et al.* (2018) conducted experiments on convective drying of potatoes at temperatures ranging from 40 to 70 °C and air velocities between 2 and 6 m s^{-1}. They observed that increasing air velocity from 2 to 6 m s^{-1} significantly reduced drying time, with optimal drying rates achieved at higher velocities within this range.[53] These studies collectively suggest that maintaining drying temperatures between 50 and 70 °C and air velocities between 1 and 2.5 m s^{-1} can optimize drying efficiency while preserving product quality.

9.4. Foam thickness and tray loading

The thickness of the foam mat, typically ranging from 2 to 5 mm, plays a crucial role in the drying rate and final product characteristics.[126] Thinner layers reduce drying time but may compromise structural stability, whereas thicker layers improve retention but extend drying duration. A foam thickness of 3 to 4 mm must be maintained for a balance between drying efficiency and powder integrity.[37] A study on the foam-mat drying kinetics of Keitt mango pulp demonstrated that increasing the foam layer thickness from 0.5 cm to 1.5 cm resulted in longer drying times across temperatures of 50 °C, 60 °C, and 70 °C.[100] The increased thickness led to greater resistance to moisture migration from the center to the surface, thereby extending the drying duration.[100] Research on foam-mat drying of carrageenan with egg white as a foaming agent indicated that a foam thickness of 4 mm achieved drying rates comparable to those of a 2 mm thick non-foamed sample.[127] This suggests that the porous structure of the foam enhances moisture diffusion, allowing for efficient drying even at greater thicknesses.[127] In the foam-mat drying of red beetroot pulp, increasing the foam thickness from 5 mm to 7 mm significantly reduced the drying rate by approximately 29.63%.[128] The study also noted that thicker foam layers led to increased surface roughness and cracking in the dried powder, affecting its flowability and microstructural properties.

9.5. Monitoring and quality control

Real-time monitoring tools such as near-infrared (NIR) spectroscopy and thermal imaging are increasingly being explored for in-line moisture analysis and hot spot detection. Moisture content, water activity (a.w.), color retention, reconstitution behavior, and nutrient profiles (*e.g.*, vitamin C and polyphenols) must be regularly evaluated using standard AOAC methods and spectrophotometric assays.[129] NIR spectroscopy has been extensively utilized for in-line moisture content analysis during drying processes. Kauppinen *et al.* (2014) validated a multipoint NIR spectroscopy method for in-line moisture content analysis during freeze-drying, highlighting its effectiveness in real-time monitoring.[130] Thermal imaging serves as a non-destructive technique to detect temperature variations and hotspots during drying. Applications of thermal imaging in food quality and safety assessment have been reviewed, emphasizing its role in monitoring and ensuring uniform drying.[131] The Association of Official Analytical Chemists (AOAC) provides standardized methods for determining moisture content and water activity, which are critical parameters in assessing the quality and shelf-life of dried products. AOAC Official Method 967.22 outlines the determination of vitamin C in vitamin preparations and juices, ensuring accurate assessment of nutrient retention post-drying.[129]

9.6. Packaging and storage

Dried powders obtained *via* FMD are highly hygroscopic and sensitive to light and oxygen. Proper packaging using vacuum-sealed aluminum laminates or inert-gas flushed pouches is critical to extending shelf life. A study evaluated the impact of different packaging materials on the color, foaming properties, and shelf life of foam-mat-dried starch–albumen powder. It was found that packaging materials with low oxygen and moisture permeability, such as aluminum foil laminates, were effective in preserving the quality of the dried powder over extended storage periods.[132] This research focused on creating a flexible, impermeable packaging sheet using aluminum foil laminated with jute web. The resulting material demonstrated excellent barrier properties against moisture and oxygen, making it suitable for packaging hygroscopic food products like FMD powders.[133]

9.7. Economic and sustainability considerations

Compared to freeze drying or spray drying, FMD is significantly more energy-efficient and cost-effective, especially for heat-sensitive, small-batch operations.[134] The use of plant-based or by-product foaming agents (*e.g.*, guar foaming albumin and chickpea protein) enhances sustainability. Making a matrix: factors such as product type, heat sensitivity, energy cost, volume, shelf life, and powder performance can be integrated into a Multi-Criteria Decision Analysis (MCDA) tool to support industrial planning and investment decisions (Fig. 3 and Table 6).[135]

9.8. Challenges and limitations in foam mat drying

While foam mat drying (FMD) presents a highly promising method for preserving liquid and semi-liquid products, its commercial application still faces several critical challenges and limitations that must be addressed for large-scale success.[138] One of the foremost concerns is scale-up feasibility. Although FMD performs efficiently at laboratory and pilot scales, translating this into a continuous, automated industrial process remains complex due to the need for uniform foam spreading, consistent drying conditions, and efficient material handling systems. Designing large-scale dryers that maintain uniform airflow, temperature control, and foam thickness across wide surfaces is technically demanding and cost-intensive. Another challenge lies in achieving batch-to-batch consistency and reproducibility.

Foam formation is highly sensitive to several variables, including the type and concentration of foaming agents, whipping time and speed, and the physical–chemical nature of the feed material. These sensitivities can lead to variability in foam properties, affecting drying kinetics, product texture, and functional quality. Furthermore, the interaction between foaming agents and the product matrix can lead to issues such as chemical incompatibility, altered taste, or degradation of active compounds. For instance, some proteins used as foaming agents may denature or react with phenolic compounds, impacting both foam stability and bioactive retention.[44]

From a sustainability standpoint, energy efficiency is another concern. While FMD reduces drying time compared to traditional methods, the initial foam generation step and the maintenance of controlled drying environments may lead to higher operational energy demands, especially if drying parameters are not optimized. Addressing these limitations will require multidisciplinary innovations in foam formulation, equipment design, real-time process control, and energy modeling. Future developments in smart foaming systems, sustainable foaming agents, and hybrid drying techniques may help overcome current barriers and unlock the full industrial potential of foam mat drying.

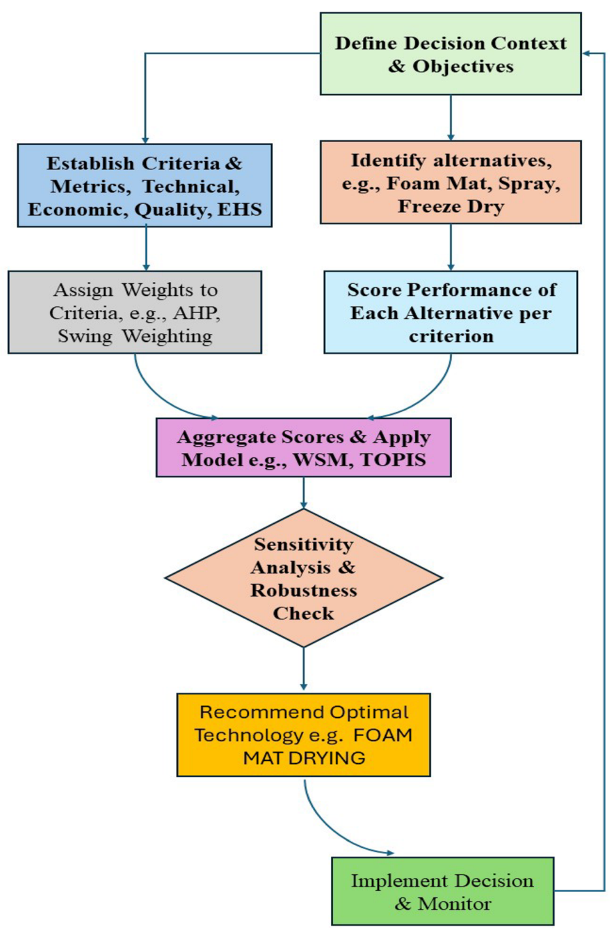

Fig. 3 The MCDA process for drying technology selection.

Table 6 Comparative economic analysis: foam mat drying *vs.* freeze-drying *vs.* spray drying

Aspect	Freeze drying (FD)	Spray drying (SD)	Foam mat drying (FMD)	Key citations
Capital cost (CAPEX)	Very high Requires sophisticated vacuum, refrigeration, and condenser systems	High Costs are driven by high-pressure pumps, atomizers, air heaters, and large powder recovery systems	Low to moderate Equipment is simpler; often a mixer and a conveyor-belt or cabinet dryer	Kudra T. & Ratti C. (2006)[134]
Energy consumption	Extremely high ~1200 kJ kg^{-1} water removed. Energy-intensive due to sublimation and maintaining a high vacuum	High ~5000 kJ kg^{-1} water removed. Inefficient due to high thermal load and large volumes of hot air required	Moderate Lower due to high drying rates, increased surface area, and lower temperatures than SD.	Kudra T. & Ratti C. (2006),[134] Stratta L. *et al.*, (2020),[136] and Al-Mansour *et al.*, (2011)[137]
Additive costs & load	Typically, low Often requires few or no carriers	Moderate to high Often requires 30–60% w/w of carriers (*e.g.*, maltodextrin) to aid drying and powder recovery	Low to moderate Requires 1–5% w/w foaming agents (*e.g.*, egg white and gums), but no need for high carrier load	Kandasamy *et al.* (2022)[52]
Overall cost per kg (context)	Very high Prohibitively expensive for most food applications	Moderate The industrial benchmark for high-volume powder production	Low to moderate Most economical for difficult-to-dry products at the pilot or medium scale	Ratti (2006)[134] and Kadam *et al.* (2010)[39]

10. Conclusion

Foam Mat Drying (FMD) stands at the frontier of modern dehydration technologies, offering a rare synergy between efficiency, affordability, and preservation of product integrity. By intelligently engineering the conversion of liquids into thin, porous foam layers, this method drastically enhances drying rates while minimizing nutrient degradation, making it especially valuable for heat-sensitive, bioactive-rich materials. From fruit purees and dairy emulsions to herbal extracts and probiotic suspensions, FMD has shown remarkable versatility across sectors, enabling the development of clean-label, shelf-stable, and rehydratable powders with high functional and sensory fidelity. The technique's strength lies in its ability to be customized at every stage from foam formation to drying kinetics, allowing fine-tuned control over the microstructure, texture, color, and rehydration behavior. However, to fully harness its industrial potential, challenges related to scale-up, reproducibility, energy optimization, and foaming agent compatibility must be strategically addressed.

As research pushes the boundaries with ultrasound-assisted foaming, bio-based stabilizers, hybrid drying approaches, and AI-driven process modeling, FMD is rapidly evolving into a next-generation platform for sustainable bioprocessing. It holds immense promise for reducing postharvest losses, enabling functional product innovation, and creating value-added solutions in both the food and pharmaceutical domains. In essence, foam mat drying is more than a drying method; it is a technology of transformation, bridging science and industry with the promise of healthier, more accessible, and longer-lasting products. With continued innovation and collaborative research, FMD is poised to redefine the future of drying in a world increasingly driven by quality, sustainability, and functional nutrition.

Author contributions

Swanand Kalambe: conceptualization, writing – original draft preparation. Sadanand Guhe: conceptualization, supervision, reviewing and editing.

Conflicts of interest

There is no conflict of interest in between authors and coauthors.

Data availability

No new data were generated or analyzed in this study. All data discussed in this review are derived from previously published sources, which have been cited appropriately throughout the manuscript.

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