

# Foaming Agents in Foam Mat Drying of Fruits: Mechanisms, Effectiveness, and Functional Applications – A Review

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## Abstract

Foam mat drying is a promising technique for producing high-quality, shelf-stable fruit powders, particularly from heat-sensitive, viscous, and underutilized fruits. This review critically examines the roles and effectiveness of food-grade foaming agents, including proteins, carbohydrates, and hydrocolloids, in enhancing foam formation, stability, and overall drying efficiency. Protein-based agents such as egg albumin, whey protein isolate, and soy protein isolate provide excellent foam expansion and structural integrity. Carbohydrate-based compounds like maltodextrin, pectin, and modified starch primarily function as stabilizers, improving viscosity and nutrient retention. Hydrocolloids such as methylcellulose, carboxymethyl cellulose, guar gum, and xanthan gum further strengthen foam structure and enhance the rehydration properties of the resulting powders. Synergistic combinations of these foaming and stabilizing agents tailored to specific fruit matrices significantly improve powder quality, solubility, and preservation of bioactive compounds. Despite advancements, key challenges remain, including the development of novel, plant-based, and allergen-free alternatives, limited application to underutilized fruits, and a lack of techno-economic and environmental sustainability assessments. This review provides a consolidated framework to guide future research and industrial applications aimed at optimizing foam mat drying for efficient, value-added, and sustainable fruit processing.

**Key words :** Foam mat drying, fruit powders, foaming agents, Drying kinetics, hydrocolloids, functional ingredients, Consumer acceptability.

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Fruit preservation remains a critical strategy for minimizing postharvest losses and ensuring nutritional security, especially given the perishability of fresh produce due to high moisture content. Drying is one of the oldest and most effective preservation methods, offering the dual benefits of shelf-life extension and the production of lightweight, easily transportable powders. However, conventional drying techniques such as hot air or sun drying often degrade heat-sensitive nutrients and compromise sensory qualities, particularly in fruits rich in thermolabile compounds like vitamin C and volatile aromas (Kandasamy et al, 2014; Hardy and Jideani, 2017).

Foam mat drying has emerged as a promising alternative, particularly for liquid and semi-liquid fruit products that are otherwise difficult to process. This technique involves

whipping fruit pulp with foaming agents: such as egg albumin, soy protein, or lecithin, and stabilizers like carboxymethyl cellulose or pectin, to create a stable foam that is then dried as a thin mat at moderate temperatures (Kandasamy et al, 2014). The increased surface area and porous structure of the foam accelerate moisture removal, significantly reducing drying time and better preserving heat-sensitive nutrients, color, and flavor compared to conventional methods (Djaeni et al, 2013). Additionally, foam mat drying is cost-effective and produces powders with excellent reconstitution properties, making it suitable for large-scale applications.

The choice of foaming agent and stabilizer is crucial for the success of foam mat drying, as these additives influence foam formation, stability, and the quality of the final powder. Protein-based agents like egg albumin and plant-

based alternatives such as soy protein isolate have demonstrated excellent foaming capacity and stability, while hydrocolloids like methylcellulose and gum arabic further enhance foam structure and prevent collapse during drying. The optimal combination of these agents depends on the specific fruit matrix and desired product characteristics, as variations in sugar content, acidity, and viscosity can affect foam behavior and drying kinetics (Ratti, 2001).

Despite the recognized advantages of foam mat drying, most existing studies focus on optimizing process parameters for individual fruits or specific foaming agents, with limited comparative analysis across different fruit types and additive combinations. There is a need for systematic reviews that consolidate current knowledge on the influence of various foaming agents on foam properties, drying efficiency, and the nutritional and sensory quality of fruit powders. Such reviews are essential for guiding researchers and industry practitioners in selecting the most suitable formulations for diverse applications and for identifying future research directions (Kandasamy et al., 2014; Hardy and Jideani, 2017).

**Foaming agents :** Foaming agents are substances, typically proteins or surfactants, that facilitate the incorporation and stabilization of air within a liquid matrix by reducing surface tension, thereby enabling the formation of uniform foams. In foam mat drying, they are essential for transforming fruit juices or purees into stable foams that enhance drying efficiency and final product quality. By lowering the surface tension at the liquid-air interface, foaming agents promote air entrapment and create a porous structure that accelerates moisture removal and improves rehydration of the resulting powder. Their role in stabilizing the foam is critical to prevent bubble coalescence and collapse during drying, preserving the integrity and consistency of the foam mat. An

effective food-grade foaming agent must be non-toxic, approved for food use, neutral in flavor, and capable of forming stable foams at low concentrations. It must also be compatible with the specific fruit matrix and processing conditions such as pH and temperature, while remaining cost-effective and industrially viable. Commonly used agents include egg albumin, whey protein isolate, soy protein isolate, and hydrocolloids like methylcellulose and hydroxypropyl methylcellulose (HPMC), each offering distinct foaming and stabilizing characteristics (Parmar et al., 2020; Ekpong et al., 2016; Djaeni et al., 2015).

### **Classification of Foaming agents:**

#### **A. Protein-Based Foaming Agents :**

Protein-based foaming agents are predominant in foam mat drying due to their exceptional ability to reduce surface tension and form stable, voluminous foams. These proteins create highly expanded, low-density foams that withstand the drying process, ensuring rapid dehydration and yielding fruit powders with preserved nutrients and favorable textures.

**1. Egg Albumin (Egg White) :** Egg albumin remains the benchmark protein foaming agent in fruit and vegetable foam mat drying. Its rapid adsorption at the air-liquid interface during whipping forms a robust, elastic film, enabling high foam expansion and low density. Foam stability is optimal around 15% concentration and 15 minutes of whipping, as these parameters resist bubble collapse and maintain foam integrity during drying, supporting efficient moisture removal and desirable powder qualities. Proper optimization is crucial, since inadequate or excessive whipping or concentration can lead to foam instability. Egg albumin's natural origin, strong foaming ability, and compatibility with diverse fruit matrices make it especially valuable (Mishra et al., 2012).

**2. Soy Protein Isolate (SPI) :** Soy protein isolate is a widely used plant-based alternative, suitable for vegan and allergen-free applications. SPI's ability to form foams results from its globular protein structure, though its stability is generally somewhat lower than animal-derived proteins, especially when exposed to heat, mainly due to the formation of insoluble aggregates. Mixing SPI with other proteins or stabilizers like maltodextrin enhances both foam formation and stability. SPI's affordability, wide availability, and applicability across various fruit pulps further support its use in foam mat drying. Innovative plant-based agents such as aquafaba have recently emerged, demonstrating good foaming capacity and promising sustainability for future applications. (Kandasamy *et al.*, 2014)

**3. Whey Protein Isolate (WPI) :** Whey protein isolate, containing over 90% protein, exhibits strong surface activity and high solubility across varying pH levels, producing foams with robust expansion, low density, and notable stability. WPI-based foams are commonly combined with maltodextrin to improve stability, reduce stickiness, and enhance the retention of bioactive and sensory compounds. These characteristics make WPI a versatile choice, particularly for health-conscious consumers and those avoiding egg allergens.

### **Carbohydrate-Based Foaming Agents**

Carbohydrate-based foaming agents, including modified starches, maltodextrin, and pectin, are generally poor foamers alone but play a vital role in foam stabilization and viscosity enhancement in foam mat drying. Used mainly in combination with proteins, they improve foam stability, prevent collapse during drying, and yield high-quality fruit powders.

**1. Modified Starch :** Modified starches serve primarily as stabilizers by increasing the viscosity of the liquid phase, which curbs liquid

drainage and minimizes bubble coalescence and foam collapse. While they do not generate foam independently, their molecular networks entrap water and support air bubbles, slowing migration and boosting gel strength. Certain varieties, such as hydroxypropylated or acetylated starches, are especially effective due to enhanced solubility, swelling, and interaction with proteins and hydrocolloids. When used with proteins or hydrocolloids, modified starches significantly improve foam stability and help produce uniform, porous, and easily rehydratable powders, especially in high-sugar or high-acid fruit matrices (Paramasivam *et al.*, 2022).

**2. Maltodextrin :** Maltodextrin is valued for its stabilizing and carrier functions. It increases the viscosity of foam mixtures, slows liquid movement, and reduces bubble collapse, which leads to denser, stable foams—especially needed for foaming low-solid fruit pulps prone to instability. When combined with proteins like whey protein isolate, maltodextrin forms protective networks around air bubbles, safeguarding sensitive bioactive compounds. Higher levels (up to 30% w/w) enhance powder texture, lower stickiness and hygroscopicity, and improve storage stability and flowability. Maltodextrin also enhances the solubility and dispersibility of fruit powders without adversely affecting their natural taste, making it ideal for instant beverage applications (Song *et al.*, 2022).

**3. Pectin :** Pectin, a natural polysaccharide from citrus and apples, is known for its gelling and stabilizing qualities. In foam mat drying, pectin increases liquid-phase viscosity, slows drainage, and prevents collapse of air bubbles, reinforcing foam structure against mechanical and thermal stresses. Its synergistic effect with proteins, such as egg albumin or whey protein, increases foam stability and can double foam volume by enhancing water binding and strengthening the film around bubbles. Especially effective for fruit pulps with high sugar

and acid content, pectin improves foam expansion, stability, texture, and rehydration properties in the resulting powder, making it suitable for clean-label and health-conscious applications (Osama et al, 2022).

### **Hydrocolloids / Gums in Foam Mat Drying**

Hydrocolloids and gums are essential stabilizers in foam mat drying, significantly enhancing foam viscosity and stability. While they do not typically serve as primary foaming agents, their ability to support and reinforce the foam matrix is critical for producing high-quality, shelf-stable fruit powders. By increasing the viscosity of the liquid phase, they slow liquid drainage and prevent bubble coalescence, ensuring a robust and uniform foam structure throughout the drying process.

#### **1. Guar Gum and Xanthan Gum :**

Guar gum and xanthan gum are two of the most widely employed hydrocolloids in foam mat drying, known for their strong water-binding and thickening properties. Both greatly increase the viscosity of foam mixtures, slowing liquid drainage to support stable air bubbles and reducing foam collapse. Guar gum, obtained from guar plant seeds, hydrates rapidly and forms viscous solutions even at low concentrations, making it especially effective for stabilizing foams in fruit matrices with high sugar or acidity. Xanthan gum, produced through bacterial fermentation, also delivers high viscosity and is stable across a wide range of pH and temperatures, enhancing the texture, solubility, and rehydration properties of fruit powder. Used together with protein-based foaming agents, these gums synergistically boost foam expansion, stability, and powder quality. Their natural origin, safety, and effectiveness make them indispensable in commercial fruit powder production (Paramasivam et al, 2022).

**2. Methylcellulose :** Methylcellulose is a semi-synthetic, water-soluble cellulose derivative

highly valued for its unique ability to form thermoreversible gels. During drying, methylcellulose undergoes thermal gelation, creating a network that stabilizes air bubbles and prevents foam collapse. This leads to low-density, highly stable foams, resulting in porous, lightweight, and easily rehydratable fruit powders, ideal for instant beverages. Its effectiveness is concentration-dependent; at optimal levels, it provides sufficient viscosity and gel strength without making the foam overly dense. Methylcellulose is often blended with proteins or other hydrocolloids to further enhance foam stability and powder texture (Osama et al, 2022).

**3. Gelatin :** Gelatin, a protein derived from collagen, functions as both a foaming agent and stabilizer, offering versatility in foam mat drying. When whipped, gelatin lowers surface tension, promoting air incorporation and forming stable foams. Upon cooling, it forms a three-dimensional gel network that supports and traps air bubbles, providing excellent foam expansion, uniformity, and resilience. Gelatin is frequently used in combination with other agents such as guar gum or modified starch to further improve the stability and quality of fruit and vegetable powders. Its ability to create stable gel networks is key for producing powders with high stability, enhanced texture, and excellent rehydration properties (Paiva et al, 2023).

### **Foaming Agents and Their Effects in Foam Mat Drying of Selected Fruits :**

Egg albumin was found effective for mango, pineapple, and muskmelon due to its high foam expansion, stability, and color retention (Gujral and Khanna, 2002; Hassan and Ahmed, 1998; Sangamithra et al., 2015). Papaya showed good foam stability and high rehydration when treated with soy protein isolate and egg albumin with CMC (Ratti and Kudra, 2006; Hao et al., 2024). Banana and gac fruit benefited from whey protein isolate, offering low density, good

reconstitution, and nutrient retention (Bhusari *et al.*, 2014; Kha *et al.*, 2010). Gelatin and guar gum provided moderate foam and acceptable taste in watermelon and orange, respectively (Jain and Pathare, 2007; Yadav *et al.*, 2012). Amla performed well with modified starch and maltodextrin, ensuring good yield and vitamin C retention (Sharma *et al.*, 2015). Guava and tomato used combinations of egg albumin and soy protein for high foam stability and short drying time (Franco *et al.*, 2015). Starfruit with soymilk resulted in porous powder and fast drying (Karim and Wai, 1999). Tropical red fruit blends using albumin and multiple gums had low water activity and high bioactive retention (Paiva *et al.*, 2023).

**Mechanism of Foam Formation and Stability in Foam Mat Drying :** Foam mat drying relies on the successful incorporation and stabilization of air within a fruit puree or juice to create a porous structure that enhances drying efficiency and preserves product quality. Understanding the interaction between foaming agents, stabilizers, and processing conditions is essential for optimizing this process. (Yuen, 2019)

**Foam Formation :** Foam formation in food systems occurs when air is dispersed into a liquid matrix through whipping or agitation, usually in the presence of foaming agents such as proteins or surfactants. These agents lower the surface tension at the air-water interface, enabling millions of tiny bubbles to form and remain suspended throughout the mixture. The effectiveness and stability of this foam depend heavily on the surface activity and adsorption characteristics of the chosen foaming agents. (Yuen, 2019).

**Protein Unfolding and Film Formation:** Proteins like egg albumin and whey protein are particularly adept at stabilizing foams. Upon whipping, these proteins migrate and adsorb

onto the surface of each air bubble. This adsorption induces partial unfolding, exposing hydrophilic and hydrophobic regions, hydrophilic groups interact with the aqueous phase, while hydrophobic groups face the air. The result is a viscoelastic, cohesive film around each bubble, which physically shields against bubble coalescence and collapse. The strength and elasticity of these interfacial films directly determine both foamability and long-term foam stability.

**Foam Stability :** Foam stability is the ability of the foam to resist structural breakdown during and after formation-a crucial factor for the success of foam mat drying. Several key physicochemical properties and operational parameters influence this stability:

**Viscosity :** High viscosity in the continuous phase, often achieved by incorporating hydrocolloids (e.g., maltodextrin, guar gum, xanthan gum), slows liquid drainage and enhances foam resilience. Increased viscosity supports a more stable foam matrix, crucial for avoiding collapse during drying and achieving powders with superior texture and rehydration characteristics.

**Surface Tension :** The reduction of surface tension by effective foaming agents allows for the rapid and uniform formation of stable bubbles. However, if surface tension is too low, bubble coalescence may accelerate, so an optimal level must be maintained for maximum stability and efficiency.

**Protein Solubility :** Proteins with high solubility, such as egg albumin and whey protein isolate, readily migrate and form strong films around bubbles, resulting in foams with exceptional expansion and stability. Less soluble proteins tend to yield poorer foam quality.

**pH and Temperature :** Both affect protein structure and foam behavior. Maintaining

optimal pH and moderate temperatures (typically 50-70°C) ensures proteins remain functional, upholds foam stability, and minimizes nutrient and flavor loss. Excessive heat can cause collapse and reduce product quality, while too low a temperature may inhibit proper drying.

**Rheological Properties** : Foam mats benefit from high viscoelasticity and yield stress,

which help the structure withstand mechanical and thermal stresses encountered during drying. Such rheological strength ensures uniform drying and formation of high-quality, porous powders.

**Bubble Size Distribution and Stabilizers** : Incorporating stabilizers and optimizing foaming conditions result in smaller, more uniform bubble sizes, which reduce

#### Comparative roles of foaming agents in foam mat drying

Foaming Agent	Stability	Foamability	Drying Effect	Typical Fruit/Matrix	Key References
Egg Albumin	High (up to 92%)	Excellent (high expansion, low density)	Rapid drying, good rehydration, superior porosity	Tomato, papaya, guava	Kandasamy <i>et al.</i> , 2014
Whey Protein Isolate (WPI)	High	Good	Produces uniform, fine powders, minimal stickiness	Tamarillo, melon, dairy	Franco <i>et al.</i> , 2015
Soy Protein Isolate (SPI)	Moderate to high	Moderate to high	Stable when combined with carbohydrates, vegan-friendly	Tomato, papaya	Franco <i>et al.</i> , 2015
Maltodextrin	Very high (as stabilizer)	Poor (not primary foamer)	Increased yield, reduced stickiness, improved shelf stability	Black plum, tomato	Islam <i>et al.</i> , 2024
Carboxymethyl Cellulose (CMC)	Very high (up to 94%)	N/A (stabilizer)	Enhances foam stability, increases final powder solubility and TSS	Tomato, papaya, guava	Hossain <i>et al.</i> , 2024
Guar Gum / Xanthan Gum	High	Poor (stabilizer)	Supports uniform structure, improved texture, resistant to collapse	Fruit, vegetable foams	Kandasamy <i>et al.</i> , 2014
Gelatin	High	Good	Dual function: forms and stabilizes foam, good resilience	Watermelon, tropical blends	Paiva <i>et al.</i> , 2023
Glycerol Monostearate (GMS)	High	Moderate to high	Enhances expansion and stability compared to CMC	Papaya	Kandasamy <i>et al.</i> , 2014
Pectin	Moderate to high	Poor (stabilizer)	Increases viscosity, prevents bubble collapse, reinforces protein foams	Kadamba fruit, blends	Osama <i>et al.</i> , 2022

gravitational drainage and coarsening effects. A more uniform foam structure supports better drying characteristics and improved final product texture.

**Water Solubility Index (WSI) and Water Absorption Index (WAI) :** The use of suitable stabilizers and careful drying conditions increases the WSI and WAI, yielding powders that dissolve quickly and rehydrate efficiently, critical attributes for instant food products.

**Color and Sensory Properties :** Stable foams and moderate drying conditions help preserve natural color, aroma, and flavor components, essential for consumer acceptance. Unstable foams or excessive heat can lead to browning, off-flavors, and nutrient loss (Kandasamy *et al.*, 2014; Yuen, 2019).

### Foam Characterization Parameters

**Foam Expansion (%) :** Measures the volume increase after whipping, indicating the extent of air incorporation.

**Foam Density ( $\text{g cm}^{-3}$ ) :** Lower values signal higher air content and thus a lighter, more aerated foam.

**Foam Stability :** Monitored over time by measuring changes in foam volume or height, reflecting the foam's ability to maintain structure during processing and storage.

### Conclusion

Foam mat drying has proven to be an efficient and scalable technique for producing high-quality fruit powders from heat-sensitive and viscous fruit matrices. This review highlights that the choice and combination of foaming agents, particularly proteins such as egg albumin and whey protein isolate, and stabilizers like maltodextrin, pectin, and hydrocolloids, play a pivotal role in determining foam expansion, structural integrity, drying kinetics, and final

product attributes. Synergistic interactions among these agents can be tailored to specific fruit characteristics to improve powder texture, rehydration, nutrient retention, and sensory quality.

Despite these advancements, several critical gaps remain. Research on novel, plant-based, and allergen-free foaming agents like aquafaba remains limited. Furthermore, few studies have addressed the techno-economic feasibility, energy efficiency, or environmental sustainability of foam mat drying at scale. Future work should explore integrated optimization approaches, including response surface methodology and machine learning tools, to fine-tune agent concentrations and drying parameters for diverse fruit systems.

Ultimately, foam mat drying offers significant potential for developing clean-label, shelf-stable, and functionally rich fruit powders. With continued innovation and interdisciplinary collaboration, this technology can contribute meaningfully to sustainable food processing and value-added utilization of underexploited fruit resources in both domestic and global markets.

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