

Research Article

Effects of Protein- and Carbohydrate-Based Foaming Agents on Foam Stability and Microstructure in Freeze-Dried Coffee

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ABSTRACT

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The development of high-quality instant coffee products is essential for increasing market accessibility and economic value for local coffee producers. This study investigates the effect of various foaming agents including maltodextrin, whey protein isolate, and egg white powder on the foam stability and microstructure of coffee extracts processed via foam-mat freeze drying. Coffee extract prepared from roasted Arabica beans sourced from Plang Yai community in Chiang Mai, Thailand, was combined with ten different formulations of foaming agents ranging from 0 – 10% (w/w) and evaluated through foam stability testing and scanning electron microscopy (SEM). The control group consisted of a sole coffee extract without foaming agents added. The results showed that egg white powder was the most effective foaming agent, yielding stable foams and uniform pore structures, particularly at concentrations above 5%. While maltodextrin and whey protein isolate alone did not produce stable foams, they enhanced structural stability when used in combination with egg white powder. SEM imaging further confirmed that the optimal formulations exhibited well-developed porous networks, crucial for drying efficiency and product rehydration. The highest foam stability (96.1%) was achieved with a balanced formulation of all three agents. These findings confirm the synergistic interaction between proteins and carbohydrates in foam stabilization, offering a robust method for producing premium instant coffee. The integration of this approach enables smallholder enterprises to expand product lines while maintaining quality, enhancing the economic sustainability of coffee farming communities.

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1. Introduction

Thailand's coffee industry has witnessed significant growth in recent years, particularly in the northern highlands, where the climate and elevation provide ideal conditions for Arabica coffee cultivation. Chiang Mai, one of Thailand's most well-known coffee-producing provinces, has a climate and elevation highly suitable for cultivating high-quality Arabica coffee. The province is home to over 8,000 hectares of coffee plantations, with annual production exceeding 6,000 tons (This Side Up, 2025). The majority of coffee farms in Chiang Mai are run by smallholder farmers, many of whom are part of local community enterprises aiming to create sustainable livelihoods through coffee production. The demand for Chiang Mai's specialty coffee has

been growing steadily, both domestically and internationally, with exports increasing by approximately 15% annually (Bangkok Post, 2024). However, despite the high-quality beans produced in the region, Plang Yai community enterprises primarily sell roasted coffee beans, limiting their access to broader consumer markets.

While roasted coffee beans generally provide better aroma and flavor, the preparation requires grinding and brewing before consumption. This might not be suitable to all potential customers. Many consumers, especially those seeking convenience, prefer instant coffee products that are ready to use. Freeze drying, also known as lyophilization, is a dehydration technique that involves freezing a material and then removing its moisture by sublimation under low pressure. This

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method is widely used in food processing due to its ability to preserve the structure, aroma, and nutrients of food products, making it particularly suitable for high-value commodities such as coffee (Bhatta *et al.*, 2020). Compared to traditional drying methods, freeze drying minimizes heat exposure, which helps retain volatile compounds responsible for coffee's flavor and aroma (Rizzi, 2016). Additionally, freeze-dried coffee exhibits improved solubility and shelf life, making it a preferred choice for instant coffee production (Chen and Zhang, 2022).

Despite its benefits, freeze drying has limitations, including high operational costs and long processing times. To improve efficiency, foam-mat drying is often employed as a pre-treatment step. Foam-mat drying involves whipping the liquid coffee extract with a foaming agent to create a stable foam structure, which is then dried at a controlled temperature before undergoing freeze drying (Anandharamakrishnan, 2019). This technique reduces drying time, enhances rehydration properties, and helps maintain the microstructure of coffee particles (Liu and Kim, 2020). The foam structure allows for uniform drying, improving the overall quality of the final product (Kaya and He, 2018).

The stability and effectiveness of the foam-mat drying process largely depend on the choice of foaming agents, which help stabilize air bubbles and prevent foam collapse. Commonly used foaming agents include maltodextrin, whey protein isolate, and egg white powder. Maltodextrin acts as a carrier and stabilizer, reducing the stickiness of coffee powder and improving its solubility (Michael, 2023). Whey protein isolate contributes to foam formation by lowering surface tension, but on its own, it provides limited stability (Waghmare and Kumar, 2024). Egg white powder, on the other hand, is the most effective foaming agent due to its high protein content, which enhances foam stability by forming a strong protein network around air bubbles (Lomakina and Míková, 2006). Studies have shown that formulations containing a combination of these three agents, particularly with a higher proportion of egg white powder, result in the most stable foams, which is crucial for efficient freeze drying (Muthukumaran *et al.*, 2021). Incorporation of the egg albumin (EA) at 4.95% concentration was found to be an optimization level for tomato powder production using foam-mat drying method (Hossain *et al.*, 2024).

By integrating foam-mat drying and selecting appropriate foaming agents, freeze-dried coffee can be produced more efficiently while preserving its key sensory and functional properties. Therefore, this study aims to evaluate the effects of different foaming agent formulations on the stability, microstructure, and overall quality of freeze-dried coffee produced from locally grown beans in Chiang Mai.

2. Materials and Methods

2.1 Coffee extract preparation

The dark roasted coffee beans according to a standard Light-Medium-Dark scale, were received from the "Plang Yai" local community enterprise. The roasted coffee beans were ground to a particle size of 400–600 µm using a burr grinder (Mahlkönig EK43, Germany) to ensure uniform extraction. A ratio of 1:15 (coffee:water, w/v) was used for the extraction process. The ground coffee was brewed using a hot water extraction method at $92 \pm 2^\circ\text{C}$ for 5 minutes. A coffee brewing system (Hario V60, Japan) was used to ensure uniform extraction. The brewed coffee was filtered using a 0.45 µm membrane filter (Millipore, USA) to remove any residual coffee grounds. The filtrate was immediately cooled to 4°C in an ice bath to prevent oxidation and degradation of volatile compounds. The cooled coffee extract was concentrated using a vacuum rotary evaporator (Büchi Rotavapor R-300, Switzerland) at 40°C under reduced pressure (100 mbar) until reaching a final total soluble solids (TSS) content of 20–25% which suitable foam-mat drying method. The TSS was measured using a hand refractometer (R10, ExTech, USA).

2.2 Foam stability of foaming agents

Foam stability was evaluated by measuring the height of the foam over time. After preparing the foam using the optimized formulation by a hand mixer (HR3741, Philips) at medium speed for 10 minutes). The generated foam was immediately transferred into a 50 mL beaker. The initial foam height (H_0) was recorded in millimeters (mm) using a ruler. Foam height was then measured at specific time intervals of 1, 5, 10, 15, and 30 minutes to assess the rate of foam collapse. The experiment was done in triplicate.

Foam stability was determined using the percentage of foam retained over time compared to the initial foam height (H_0). The experiment was carried out in a controlled environment with minimum airflow at temperature $25 \pm 2^\circ\text{C}$. The foam stability percentage at a given time (H_t) was calculated using Equation (1).

$$\text{Foam Stability}(\%) = (H_t/H_0) \times 100 \quad (1)$$

where H_0 = Initial foam height, (mm)

H_t = Foam height at a given time, (mm)

2.3 Freeze drying of coffee extract using foam-mat method

2.3.1 Optimization of foam formation in coffee extract using foaming agents

The experimental set was developed using Response Surface Methodology (RSM), specifically a Constrained D-optimal Mixture Design, to optimize the interaction between the three independent variables: maltodextrin (General Chemical, China) and whey protein isolate (KC, USA) and egg white powder (Lanagrow, Thailand). The independent variables included

varying concentrations of maltodextrin (1.9–9.6%), whey protein isolate (1.9–9.6%), and egg white powder (2.2–10%), resulting in 10 experimental treatments as shown in Table 1. Additionally, four control samples (C1–C4) were prepared, including a blank and individual component references. These concentration ranges were selected based on previous studies on coffee foams, such as Maciel *et al.* (2022), have demonstrated effective foam stability at lower protein concentrations (approx. 1.5–3.0%), guiding our selection of the lower experimental limits. The upper limit of ~10% was established to avoid excessive viscosity and foam density, which have been reported to interfere with moisture removal during freeze-drying and result in poor rehydration properties in similar food matrices (Hamad *et al.*, 2024). The experiment began with weighing the

required amount of egg white powder according to the specified formulation. Distilled water (175 mL) was then added to the egg white powder and mixed using a high-speed hand mixer for 2 minutes to initiate foam formation. After this initial foaming stage, the measured amounts of maltodextrin and whey protein were incorporated into the foamed mixture, followed by an additional 2-minute mixing period to enhance foam stability. Once the foam was sufficiently developed, 30 mL of coffee extract was prepared separately and gently combined with the foamed mixture to ensure uniform dispersion without disrupting the foam structure. The final mixture was then transferred into a transparent storage container and placed in a freezer at a controlled temperature of -18°C to -20°C prior freeze-drying.

Table 1 Different percentages of foaming agents.

Sample No.	Maltodextrin (%)	Whey Isolate (%)	Egg White Powder (%)
C1 (Blank)	0	0	0
C2	6.8	0	0
C3	0	6.8	0
C4	0	0	6.8
1	2	6	10
2	1.9	9.6	9.6
3	6.5	2.2	2.2
4	6	2	10
5	6	6	6
6	5.8	5.8	9.6
7	9.6	1.9	9.6
8	9.6	5.8	5.8
9	9.3	5.6	9.3
10	9.3	9.3	5.6

2.3.2 Freeze drying condition

The freeze-drying process was conducted using a vacuum freeze dryer (Food industry model, Kinetic Engineering Co., Ltd). The sample was initially frozen at -20.0°C for 60 minutes, with a ramp time of 20 minutes under atmospheric pressure (0.0 Pa vacuum). During the primary drying phase, the temperature was gradually increased to -20.0°C over 20 minutes, held for 60 minutes, then raised to -10.0°C over 20 minutes and maintained for 100 minutes, all under a vacuum of 20.0 Pa. In the secondary drying phase, the temperature was increased to +10.0°C over 20 minutes with a 100-minute hold time, then further increased to +40.0°C over 200 minutes, followed by a 1000-minute hold time, under 20.0 Pa vacuum.

Finally, the temperature was maintained at +40.0°C for an additional 1000 minutes under the same vacuum conditions until the final moisture content was less than 5%. The dried coffee sample was then collected and stored in airtight containers at room temperature (25±2 °C) until further analysis

2.4 SEM condition

The surface morphology of the samples was observed using a Scanning Electron Microscope (SEM, ThermoScientific: Prisma E). Imaging was performed at a high voltage (HV) of 10 kV with magnifications of 70× and 200× to examine the structural features of the samples.

2.5 Statistical analysis

The statistical analysis of variance using one-way analysis of variance (ANOVA) was conducted to assess variability. Furthermore, the significant differences in means among individual treatments were evaluated using Tukey's test at a confidence level of 95% ($p < 0.05$). The analysis was performed using Minitab v.21 software (USA), and each experimental condition was replicated three times. The data were presented as the mean values and the standard deviation errors.

3. Results and Discussion

3.1 Percentage of foam stability with various foaming agents

The foam stability results reveal that the presence and composition of foaming agents significantly influence foam retention as shown in Figure 1. The control samples (C1, C2, and C3) without egg white powder exhibited zero foam stability, indicating that maltodextrin and whey isolate alone do not contribute to foam formation. However, C4, which contained 6.8% egg white powder without other stabilizers, achieved a foam stability of 76.8%, demonstrating the critical role of egg white proteins in foam formation.

Among the tested formulations, sample 10 exhibited the highest foam stability at 96.1%, followed closely by sample 9 (94.3%) and sample 7 (92.3%). These samples contained a relatively high proportion of all three foaming agents, with maltodextrin and egg white powder concentrations ranging from 5.6% to 9.6%. This suggests that optimal foam stability is achieved when all three components are present in appropriate proportions, particularly when egg white powder is maintained above 5%.

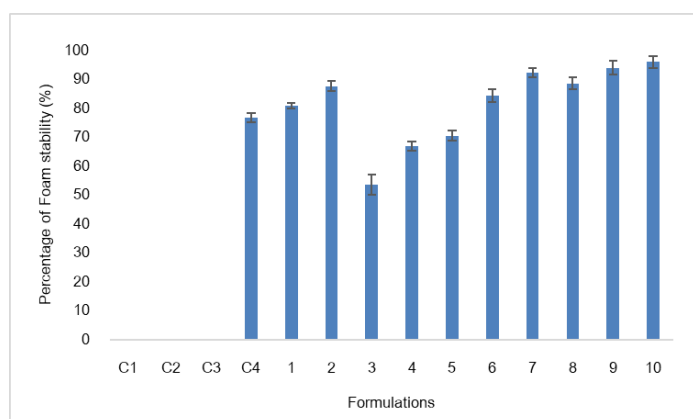


Figure 1 Foam stability (%) of freeze-dried coffee prepared with different proportions of foaming agents.

Moderate stability was observed in samples with lower total foaming agent concentrations, such as sample 5 (70.2%) and sample 4 (67.3%), where maltodextrin and whey isolate were present in smaller amounts alongside egg white powder. Notably, sample 3, which contained a higher proportion of maltodextrin (6.5%) but minimal egg white powder (2.2%), resulted in the lowest stability (54%), indicating that excessive

maltodextrin without sufficient protein-based stabilizers negatively affects foam retention.

Overall, these findings confirm that egg white powder plays a fundamental role in foam formation, while the combination of maltodextrin and whey isolate further enhances stability when used in balanced ratios. The highest foam stability (above 90%) was consistently observed in formulations with all three foaming agents present at relatively high levels, reinforcing the importance of ingredient synergy in optimizing foam retention.

The observed necessity of stabilizers is consistent with findings in similar processing contexts. Maciel *et al.* (2022) demonstrated that the use of stabilizers, particularly whey protein and maltodextrin, was crucial not only for foam integrity but also for improving the overall drying kinetics and the quality characteristics of the final coffee powder.

The findings underscore a critical synergistic effect wherein maltodextrin and whey isolate act as structural and stabilizing agents rather than foaming initiators. The supporting evidence from Ganaie *et al.* (2021) illustrates that whey protein conjugated with maltodextrin via Maillard reactions enhances functional properties like emulsification and solubility-traits beneficial for foam stabilization under processing stress. Similarly, Xiang *et al.* (2021) showed that combining whey protein and maltodextrin through freeze-drying significantly improved the stability of encapsulated probiotics, a phenomenon that parallels the improved foam integrity observed in multi-agent systems.

Moreover, the formulation containing 6.5% maltodextrin with only 2.2% egg white powder resulted in the lowest foam stability (54%), reinforcing the idea that an excessive carbohydrate component without adequate protein undermines the interfacial strength needed to retain air bubbles. This is supported by findings in Poopan *et al.* (2024) study, where maltodextrin beyond 5% did not enhance bioactive retention unless paired with protein-rich compounds, again illustrating its limited effect when used alone. This also supported by a study of Hamad *et al.* (2024), studying the effect of foaming agents in red dragon fruit powder, concluded that the type and ratio of foaming agents directly impact the final powder's physicochemical properties, including bulk density and antioxidant retention. Specifically, they found that higher protein content was essential for creating the low-density foam structure necessary for efficient drying. The poor stability observed in our high-maltodextrin, low-protein sample (6.5% maltodextrin, 2.2% egg white) is therefore consistent with the understanding that foam strength is determined by the protein's ability to create a viscoelastic film around air cells, which carbohydrates can support but not initiate.

The synergistic effect between these components where protein unfolding at interfaces, viscosity increase from carbohydrates, and potential Maillard reaction contributions suggested a multi-level mechanism where protein content

contributed to foam formation, and carbohydrate-protein interactions stabilize the formed structure. In summary, the results affirm that achieving optimal foam stability in food systems relies on both the presence of a strong foaming agent like egg white powder and the complementary structural and functional support provided by whey protein and maltodextrin in appropriate ratios.

3.2 Observation of physical appearance of freeze-dried coffee samples using SEM

SEM analysis revealed that foam morphology was significantly influenced by the relative concentrations of maltodextrin (MD), whey protein isolate (WPI), and egg white powder (EWP) (Figure 2). Among the control samples, C1 (without foaming agents) exhibited a compact, non-porous

structure, serving as a reference for non-aerated material. C2 (MD only) produced a fine but shallow porous structure. While MD contributed to a more viscous medium, its ability to generate or maintain foam structures was limited, consistent with its role as a bulking and film-forming agent rather than a foaming agent (Ratti, 2001). In contrast, C3 (WPI only) showed larger, less uniform pores with some collapse, illustrating that while WPI facilitates foam formation due to its amphiphilic nature, its foams are generally less stable without the presence of a secondary stabilizing agent (Dickinson, 2003). The most stable and uniform foam among the controls was observed in C4 (EWP only), characterized by well-defined, rounded pores. This agrees with prior studies citing EWP's superior surface activity and strong network formation at the air-water interface (Mine, 1995).

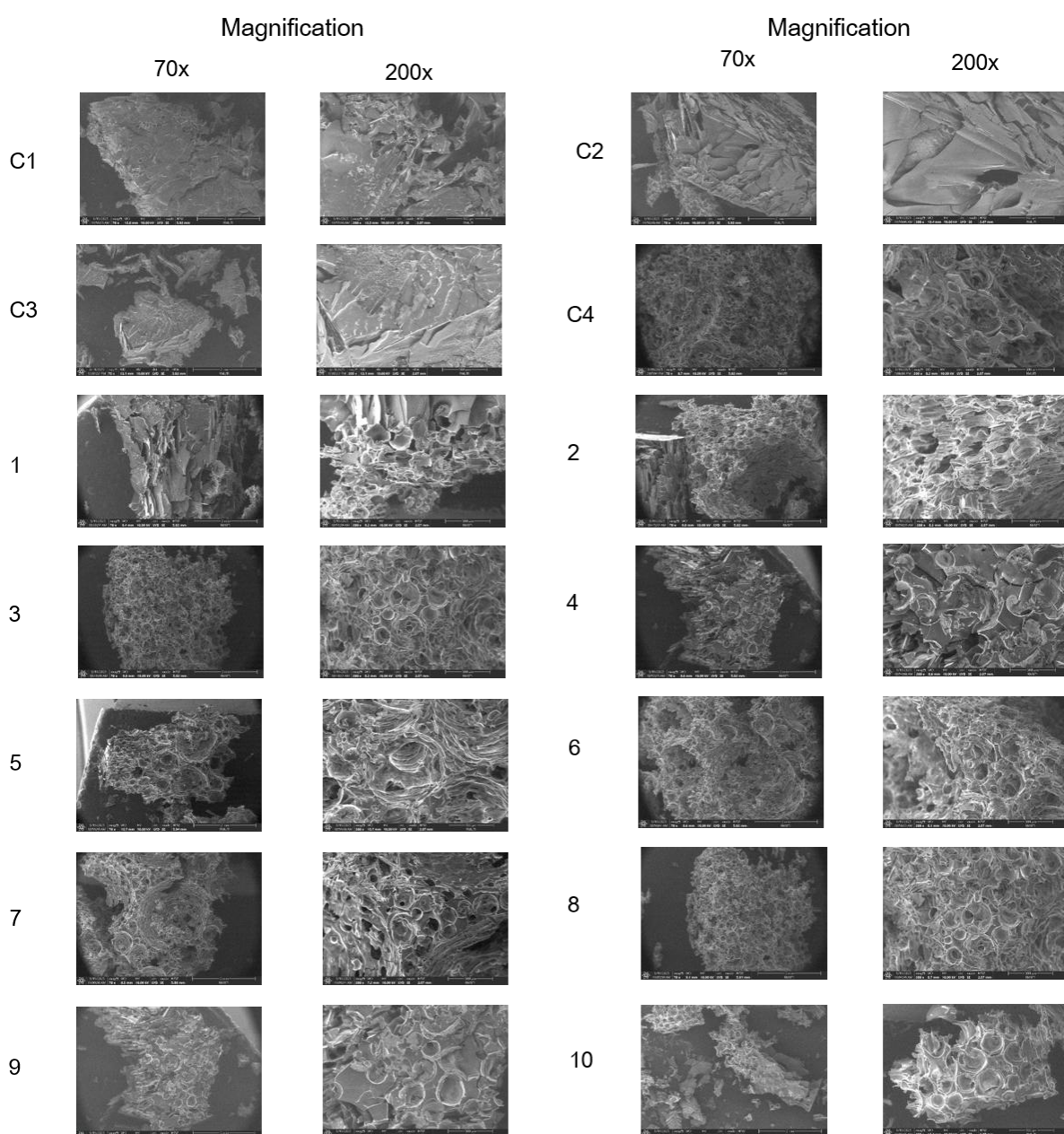


Figure 2 SEM images showing the surface structure and porosity of 14 samples with varying proportions of foaming agents at 70x and 200x magnification.

The experimental formulations presented a range of foam structures, from highly porous and interconnected matrices to dense, minimally foamed textures. Samples with a high proportion of EWP, particularly when combined with moderate amounts of WPI and low to mid-levels of MD, exhibited the most desirable foam properties. Sample 1, which included EWP at its highest ratio with supportive levels of WPI and MD, demonstrated a highly stable and porous foam with well-distributed, spherical pores. This highlights a synergistic interaction where WPI promotes foam expansion and EWP provides stabilization, while MD acts as a rheological modifier without inhibiting structure formation (Campbell and Mougeot, 1999). Similar to Sample 4, where EWP remained dominant despite higher MD content, resulting in well-maintained pore architecture. On the other hand, samples where MD was the dominant component, such as Samples 3, 7, and 8, showed denser structures with reduced porosity or evident pore collapse. This supports the notion that excessive MD impairs foam expansion by excessively increasing the viscosity of the continuous phase, which restricts air incorporation and foam elasticity (Ozcelik and Kulozik, 2023).

Comparative trends also suggest that a balanced mixture of all three agents, such as in Sample 5, produced stable foam structures with moderate pore size and uniformity. This formulation avoided the extremes of either over-stiffening (due to MD) or collapse (due to excessive protein content), offering a structurally coherent foam. Interestingly, when WPI was increased disproportionately, as seen in Sample 2, the structure showed signs of pore deformation and partial collapse, implying that although WPI enhances foam volume, it does not necessarily improve foam stability unless complemented by EWP. Similarly, in high-MD systems where EWP was present in moderate quantities (e.g., Sample 10), the presence of WPI appeared to mitigate structural degradation to a degree, although not as effectively as in EWP-rich formulations. Collectively, the data confirm that EWP plays a dominant role in foam stability and integrity, while WPI contributes to foamability and MD must be carefully regulated to avoid over-thickening the matrix (Raikos *et al.*, 2007).

4. Conclusion

This study demonstrates that the selection and ratio of foaming agents significantly influence foam stability and microstructural integrity in freeze-dried coffee production using the foam-mat method. SEM analysis confirmed that formulations with higher concentrations of egg white powder yielded well-structured, stable foams with uniform pore distribution. Maltodextrin and whey protein isolate contributed to structural integrity and viscosity modulation but were ineffective as standalone foaming agents. The highest foam stability was achieved in samples containing balanced amounts of all three agents, particularly where egg white powder exceeded 5%.

These findings underscore the synergistic role of protein-based foaming agents supported by carbohydrates in forming and stabilizing foam matrices during drying, thereby providing a critical foundation for optimizing the integrated foam-mat and freeze-drying techniques. This optimized approach presents a highly viable method for producing high-quality instant coffee while preserving aroma, solubility, and structure, offering significant benefits to community enterprises like Plang Yai by enabling value-added processing of locally grown coffee.

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