

Application Report

Application report: AR302

Industry section: Food and Beverage

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Date: 09/2025

Method: 

Keywords: Milk foam, plant milk, foam structure, foam stability



Dynamic Foam Analyzer – DFA100

Foaming Behavior of Plant-Based Milks

Comparative analysis of plant milk formulations using sparging and automatic steam frothing methods

Plant-based milks are playing an increasingly important role in the production of milk foam beverages. While there is little scope changing the composition of cow's milk to influence its foaming behavior, plant-based milks (PBM) differ markedly in their foaming behavior due to variations in protein, fat, and stabilizer composition. To optimize foam properties such as bubble size and stability—and ultimately the taste experience – it is necessary to measure these properties reproducibly.

For this study, nine commercial formulations were assessed under controlled and barista-style conditions with a KRÜSS DFA100. The results presented here enable a clear distinction between the foam properties of products based on different plants (oat, soy, pea, almond) as well as different oat-based milk recipes.



Background

The rising demand for plant-based beverages has made PBM mainstream, particularly in café and specialty coffee environments. Consumers increasingly expect plant-based formulations to replicate the sensory and aesthetic qualities of dairy milk, especially the fine, creamy foam in drinks such as lattes and cappuccinos. Foam quality is closely linked to consumer perception of beverage quality and overall satisfaction [1-4].

Achieving consistent foam in PBM is more challenging than in dairy milk [4-5]. Dairy proteins, such as casein and whey, naturally stabilize air bubbles, whereas plant-based proteins from oat, soy, almond, and pea interact differently at the air-liquid interface. Lipid content, stabilizers, and other

functional additives further influence foam formation, volume, and stability. Additionally, variations in processing and temperature during barista-style preparation can affect foam performance. These compositional and functional differences make systematic evaluation of PBM foaming properties critical for product development and quality control. This work aims to quantify differences between PBMs and provide actionable insights for optimizing formulation performance and consumer experience.

Experimental section

Samples

This study focuses on commercially available PBMs, encompassing oat, soy, almond, and pea-based formulations, which represent the major product categories across global markets, though their relative popularity differs regionally. Within the oat category, multiple brands and product types were selected to capture variations among products with similar base ingredients.

The milk compositions encompassed a range of protein concentrations (2-12 %), fat sources (rapeseed or sunflower oil), stabilizers (e.g., Gellan, Guar), acidity regulators, minerals, and natural flavorings. All samples were tested as received without further modification.

Table 1: List of investigated milks with ingredients.

Milk product (German)	Plant base	Ingredients
Oatly Barista Edition	Oat	Water, oat (10 %), rapeseed oil, potassium phosphate, calcium carbonate, potassium iodide, salt, vitamins. Fat content 3.0 %.
Oatly fettarm (= low fat)	Oat	Water, oat (10 %), rapeseed oil, potassium phosphate, calcium carbonate, potassium iodide, salt, vitamins. Fat content 1.5 %.
Berief Bio Barista Hafer	Oat	Water, whole grain oats (12 %), soy beans (2 %), sunflower oil (2 %), sea salt. Fat content 2.0 %.
Alpro Barista Hafer	Oat	Water, oat (10 %), sunflower oil, chicory root fibers, pea protein, potassium phosphate, sea salt, vitamins. Fat content 3.0 %.
Edeka Bio My Veggie Barista Hafer	Oat	Water, oat (10 %), soy beans (2 %), sunflower oil (2 %), sea salt. Fat content 2.0 %.
DM Bio Soja Drink Natur	Soy	Water, soy beans (8 %). Fat content 1.9 %.
Alpro Barista Soja	Soy	Water, soy beans (8.7 %), sugar, potassium phosphate, calcium carbonate, sea salt, gellan, natural aromas, vitamins. Fat content 1.9 %.
Vly Barista Erbsenprotein	Pea	Water, rapeseed oil, pea protein (2.5 %), fermented rice, potassium phosphate, calcium carbonate, citrus fibers, sea salt, natural aromas, potassium iodate, sodium selenate, vitamins. Fat content 3.2 %.
Alpro Barista Mandel	Almond	Water, almond (2.5 %), sugar, fructose, potassium phosphate, calcium carbonate, natural aromas, gellan, guar gum, sea salt. Fat content 1.2 %.

Preparation and measuring methods

Foam structure was evaluated under two preparation conditions using the DFA100 Dynamic Foam Analyzer with FSM Foam Structure Module (Figure 1).

In the first method, referred to as sparging, foams were generated using the sparging module of the DFA100. Prior to each measurement, 50 mL of sample was preheated to 60 °C in an oven and then

filled into a prism glass column (CY4573) equipped with a sparging holder (SH4511). Air from the internal source was sparged through filter paper (FL4551) until a defined gas volume of 45 mL had been introduced, ensuring reproducible bubble nucleation. Foam structure was recorded by camera imaging for over a period of 10 minutes considering the average time for beverage consumption. Measurements were carried out in duplicates, and representative datasets are presented.

In the second method, milk was frothed using a Cappuccinatore CS20 (Nespresso) to represent a preparation process closer to typical beverage frothing. Room-temperature milk was loaded into the canister and aerated through 2-3 preliminary cycles until stable foam was produced. The frothed milk, which typically reached a temperature of 75 – 80 °C during this process, was collected in a 250 mL beaker. Following frothing, the sample was carefully transferred into the DFA100 measurement column, with a large syringe used to remove excess liquid volume before analysis. Foam structure was then measured using DFA100.

Both methods were designed to replicate realistic café preparation conditions, enabling comparative assessment of the foams' structural stability across the different PBM formulations.



Figure 1: Dynamic Foam Analyzer – DFA100 with FSM Foam Structure Module

Results

Sparging Experiments

Structural development during sparging, evaluated through mean bubble area (MBA, Figure 2) and bubble count (BC), showed clear and formulation-

dependent differences across the PBM (Table 2). All samples exhibited the expected trend of decreasing BC and increasing MBA over the 600 s measurement, but the rate and extent of these changes varied substantially.

Almond milk showed the most pronounced structural coarsening. It displayed the lowest BC values across the entire measurement and a rapid enlargement of bubbles, with MBA values rising into the >300,000 μm^2 range by 600 s. In contrast, both soy-based milks, as well as the pea-based milk, exhibited much slower structural evolution. Their MBA values remained below roughly 135,000 μm^2 at 600 s and BC stayed comparatively high, decreasing only to around 7–10 mm^{-2} . These samples retained a high population of small bubbles throughout the test, consistent with a finer overall structure.

The oat-based milks covered the broadest range of structural outcomes. Representative ADVANCE software image analysis of oat milk foams at 1 min and 5 min of sparging (Figure 3) illustrates the evolution of foam structure, showing progressive bubble enlargement and a reduction in bubble density with increasing foam age. Early-time BC values were generally higher for these samples, often falling in the 20–30 mm^{-2} range at the beginning of the test, but they declined sharply over time. By 600 s, most oat milks had BC values below 4 mm^{-2} . Their MBA values spanned a wide interval: some samples, such as Berief and Edeka, reached values around 290,000–320,000 μm^2 , whereas Alpro showed the strongest coarsening within the oat group, exceeding 380,000 μm^2 at 600 s. The Oatly products also exhibited substantial coarsening, with final MBA values above 260,000 μm^2 and BC settling around 3–4 mm^{-2} .

Overall, the structural data from Table 2 indicate that while all formulations follow similar qualitative coarsening trajectories, the magnitude of bubble growth and BC decay differs significantly between milks, with soy showing the slowest structural changes, closely followed by pea-based milks, with almond and several oat samples showing the strongest.

Table 2: Variation of BC and MBA over time for different milk samples.

Milk product (German)	Plant base	MBA t=20 s 10 ³ μm ²	MBA t=600 s 10 ³ μm ²	BC t=20 s mm ⁻²	BC t=600 s mm ⁻²
Alpro Barista Soja	Soy	43	114	23.3	8.8
Alpro Barista Mandel	Almond	11	312	8.8	3.2
DM Soja Drink Natur	Soy	40	103	25.1	9.7
Vly Barista Erbsenprotein	Pea	43	136	23.1	7.4
Alpro Barista Hafer	Oat	37	387	27.4	2.6
Edeka Bio My Veggie Barista Hafer	Oat	83	323	12.0	3.1
Berief Bio Barista Hafer	Oat	54	297	18.5	3.4
Oatly fettarm (= low fat)	Oat	73	267	13.7	3.7
Oatly Barista Edition	Oat	80	264	12.6	3.8



Figure 2: Variation of mean bubble area (MBA, μm²) over time for different PBM samples measured with the DFA100 sparging method.

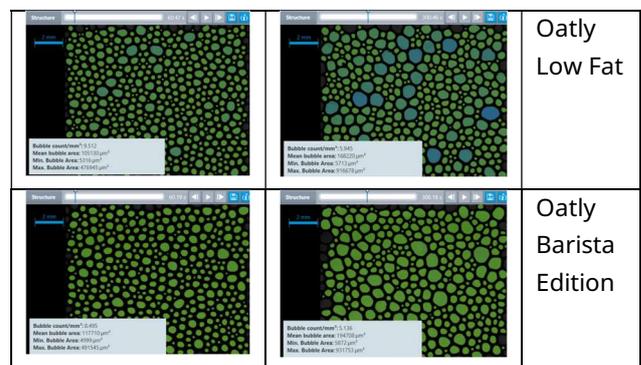
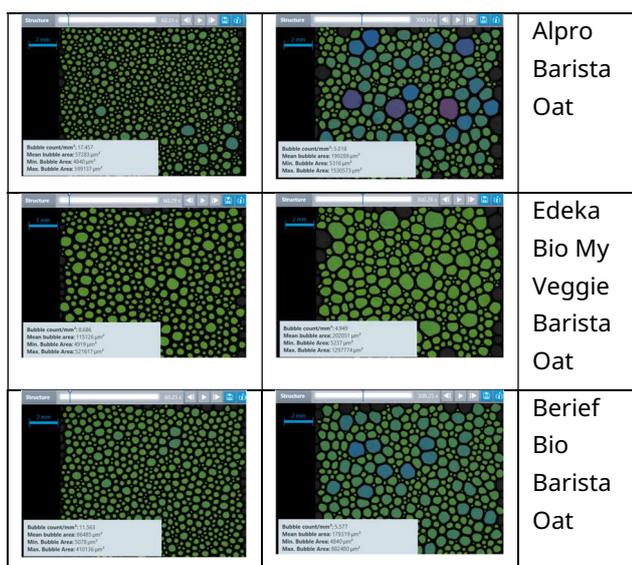


Figure 3: Oat milk samples image analysis at 1 min (left) and after 5 min (right).



Automatic steam frothing-based foams

Foams generated using the automatic steam frothing method followed similar trends to the sparging results. The mean bubble area increased throughout the measurement for all samples (Figure 5), with the fastest increase observed in oat-based milks, several of which exceeded 200,000 μm² during the analysis. Soy-based samples maintained substantially smaller bubble sizes, remaining below 80,000 μm² for most of the evaluation period. Pea-based milk showed intermediate structural development.

Initial bubble count values were higher with Automatic steam frothing than with sparging, reflecting more efficient bubble generation under the steam-air mixing process (data not shown). However, BC decreased more rapidly for oat-based samples, particularly those without protein supplementation, whereas soy-based milks retained relatively high BC values for longer. While for most

milks the overall trend remained the same as for sparging experiments, there were two distinct exceptions. The sample “Alpro Barista Mandel” (= *almond*), while showing a strong coarsening in the sparging experiments, was, under steam frothing conditions, comparable in bubble size stability to soy products. Additionally, the sample “Oatly fettarm” (= *low fat*), which was among the structurally most stable milk samples under sparging conditions, shifted to be among the two strongest coarsening samples under steam frothing conditions.



Figure 4: Mean bubble area (MBA, μm^2) vs. time for foam generation using automatic steam frothing.

Discussion

The results from both sparging and automatic steam frothing demonstrate that the foaming behavior of PBM is governed primarily by the interplay of proteins, lipids, and hydrocolloids, each contributing differently to film formation, bubble stabilization, drainage behavior, and resistance to coarsening.

Across all measurements, soy formulations consistently generated the finest and most persistent foam structures. Their relatively small MBA values and comparatively high BC throughout the measurement indicate that the interfacial layers formed by soy proteins remain cohesive over time, delaying coalescence and drainage. Soy proteins are known to adsorb quickly and form viscoelastic films around bubbles, creating a robust foam matrix [6].

Pea-based milk showed intermediate performance. Although pea proteins can form interfacial films with reasonable stabilizing ability, their interfacial elasticity is typically lower than that of soy. This difference was reflected in the structural data, where the pea sample exhibited moderate bubble enlargement and a clear reduction in bubble count

over time, yet remained more stable than almond and several oat-based samples.

Almond milk exhibited the strongest coarsening of all samples under sparging conditions. Despite maintaining a visually large foam column, its structural metrics showed rapid bubble growth and a pronounced decrease in bubble number. This outcome is characteristic of systems where foam volume is supported largely by viscosity and stabilizers rather than by strong interfacial protein films [7]. With relatively low protein content and a structural framework driven by hydrocolloids, almond milk was able to create a large amount of foam but could not maintain fine bubble structure over time. Why this behavior changed under steam frothing conditions remains unsolved.

The oat-based milks showed the greatest formulation-dependent variation. The large spread in the final MBA and BC values among oat milks emphasizes the sensitivity of oat-based foams to compositional adjustments such as added proteins, oil content, and hydrocolloid type. While some barista-style oat formulations approached the stability of the soy-based systems, others coarsened nearly as rapidly as the almond sample under sparging conditions. These differences underline the need for careful formulation design in oat-based products to achieve barista-relevant foam properties. These structural differences correlate directly with sensory performance in café-style beverages. Foams composed of small, densely packed bubbles provide a smoother and creamier mouthfeel because the fine microstructure creates a continuous, stable interfacial network that resists rapid collapse. Such foams retain flavor and lipids more effectively, enhancing perceived sweetness, richness, and overall beverage body [4, 8-9]. They also support latte art definition and persistent surface patterns. In contrast, coarse foams collapse more rapidly, drain faster, and create a thinner, airier texture with reduced flavor intensity. Thus, the structural parameters observed in the MBA and BC measurements translate directly into the sensory qualities experienced by consumers, with the most stable, fine-bubble systems particularly soy and the better-performing oat formulations delivering the desired micro foam characteristics for barista applications.

Conclusion

This study demonstrated that PBM differ markedly in their ability to generate and stabilize foam under both controlled sparging and Automatic steam frothing preparation. Soy-based milks consistently produced the finest and most stable foams. Pea-based formulations showed intermediate performance, with moderate MBA growth and BC decay reflective of their distinct but less elastic interfacial protein films.

Oat-based milks exhibited the widest formulation-dependent variation. Several commercial products showed rapid coarsening. In contrast, barista-style oat formulations supplemented with proteins and optimized lipid-hydrocolloid systems performed substantially better, achieving slower structural degradation.

The fine microfoam structures observed in the best-performing samples correlate directly with desirable sensory attributes such as creaminess, flavor retention, and improved mouthfeel, underscoring the relevance of structural metrics such as MBA and BC for predicting consumer experience [4, 8-9].

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