Green-Light Your Product: Characterizing Plant-Based Milk Alternatives with Laser Diffraction

Relevant for: dairy substitutes, sustainable diet, laser diffraction, PSA, particle size, colloidal stability

Plant-based milks have a much lower environmental impact than dairy milk, but also a more complex manufacturing process. Their mouthfeel as well as their stability is strongly correlated to the size of the dispersed particles. Here, the PSA is used to characterize the particle size distribution of oat, soy and almond milk, highlighting differences in manufacturing processes.

Product [1 L]	Greenhouse gas emissions [kgCO₂ eq]	Land use [m²]	Water use [Liters]	Eutro-phication [g PO₄]
Dairy milk	3.15	8.95	628.2	10.65
Oat milk	0.9	0.76	48.2	1.62
Rice milk	1.18	0.34	269.8	4.69
Soy milk	0.98	0.66	27.8	1.06
Almond milk	0.7	0.5	371.5	1.5

Table 1: Environmental impact of dairy milk compared to plant-based milk. Values for 1 liter of product, data from year 2013. Adapted from (1).

1 Introduction

While dairy milk remains a dietary staple in many countries, recent years have seen a dramatic increase in the manufacturing and consumption of plant-based milk alternatives. These beverages can be derived from grains (such as oat and rice), but also from beans (soybeans, peas), nuts (almonds, hazelnuts, cashew, coconut) and even seeds (hemp, flaxseed).

Many consumers choose a plant-based alternative to dairy milk on health grounds, such as caloric reduction, lactose intolerance, or milk protein allergy. But the most compelling argument in favor of plant-based milks is surely their reduced environmental impact. Indeed, greenhouse gas emissions for a liter of plant-based milk are only a fraction of that of dairy milk, while land use, water use and soil eutrophication are also very significantly reduced (see Table 1).

Manufacturing plant-based milk can, however, be very challenging. The basic process is relatively universal, requiring either wet grinding (soaking and grinding of the basis product) or the re-hydration of dry-milled powders (whole flour, dry protein concentrate), followed by the filtering out of particulates. But further manufacturing steps diverge enormously between milk types and manufacturers.

Soy milk, an Asian staple with a long tradition, has natural organoleptic properties that need to be significantly modified in order become acceptable to the majority of consumers. Removal of the so-called antinutritional factors can involve different physical or chemical treatments, as well as biotechnological intervention (fermentation, enzymatic processing) (2). More recently developed products, such as oat-based milk, are inherently unstable and require complex enzymatic hydrolysis steps, as well as the addition of stabilizers and/or thickening agents (3). Milks extracted from nuts (almond, coconut) have a high lipid content and suffer from low colloidal stability, often requiring the addition of emulsifier. These products are also frequently supplemented with nutrients to ameliorate their nutritional profile, e.g., oil added to the otherwise low in fat grain-based milk, leading to more colloidal stability issues.

Overall these highly processed products require a tight quality control at several steps of the manufacturing chain. Stability of plant-based milks is to a large extend correlated to the size of the dispersed particles (starch grains, proteins, fat globules). Hence a fast and highly reproducible particle sizing technique such as laser diffraction is useful not only to determine the efficiency of the grinding and filtering steps, but also to assess the mouthfeel and shelf life of the beverage.

2 Experimental Setup

2.1 Samples

Commercial, unsweetened and unflavored oat, soy and almond milk samples were purchased locally. Both oat milk samples stemmed from the same manufacturer, with one labelled "Classic" and the other termed "Barista". The composition of all 4 samples, as given by their respective manufacturers, is detailed in Table 2 below.

	Oat milk "Classic"	Oat milk "Barista"	Soy milk	Almond milk
Ingredients list	Water, oats (10 %), rapeseed oil, minerals, salt, vitamins.	Water, oats (10 %), rapeseed oil, dicalcium phosphate, minerals, salt, vitamins.	Water, soy beans (11 %)	Water, almonds (5 %), guar gum, salt
Nutritional values (per 100 mL)				
Fat	1.5 g	3.0 g	2.7 g	2.7 g
Carbo-hydrates	7.2 g	7.1 g	1.0 g	0.7 g
Proteins	1.1 g	1.1 g	4.6 g	1.0 g

Table 2: Ingredients list and nutritional values of the plant-based milk samples, as stated by the manufacturer.

2.2 Measurement Setup

Measurements were performed on a PSA 1190 L/D in liquid mode, using water as dispersant. Full measurement parameters are detailed in Table 3 below. The Mie reconstruction mode was chosen for the analysis, using the material refractive index of the main component of the product (starch for oat milk, protein for soy milk, oleic acid for almond milk).

Parameter	Oat milk (classic/barista)	Soy milk	Almond milk
Stirrer speed	Slow	Slow	Slow
Pump speed	Slow (45 rpm) or medium (120 rpm)	Slow (45 rpm) or medium (120 rpm)	Slow (45 rpm) or medium (120 rpm)
Reconstruction mode	Mie	Mie	Mie
Analysis mode	General	General	General
Material name	Starch	Protein	Oleic acid
Material refractive index	1.53	1.48	1.463
Material absorption index	0.01	0.1	0.01

Table 3: Measurement parameters

3 Results and Discussion

3.1 Colloidal Stability of the Samples

A simple assessment of the samples' colloidal stability was performed by visual inspection of the products after a resting time of 24 hrs. at 4 °C.

As shown in Figure 1 below, the oat milk "Classic" undergoes a strong phase separation, with a sedimented phase material representing ca 35 % of total volume, overlaid by a transparent supernatant. A sedimented phase is also visible in the oat milk "Barista", representing ca 28 % of the total volume, with an opaque supernatant. This suggests that the barista oat milk has a significantly better colloidal stability than the classic oat milk, even though it also undergoes phase separation.

No phase separation could be observed in the soy milk, suggesting an excellent colloidal stability. The almond milk underwent a minor dephasing, with a transparent (likely oil) phase visible after 24 hrs., representing less than 5 % of the total volume.

Figure 1: Plant-based milk samples photographed after resting 24 hrs at 4 °C. Phase separation interfaces are highlighted by the red dotted ellipses.

3.2 Oat Milk Measurements

The oat milk "Classic" lists rapeseed oil as the 3rd ingredient by quantity, with no listed addition of emulsifier (see Table 2). In order to potentially detect unstable oil droplets, and hence best assess the colloidal stability of the product, samples were first measured using the slowest pump setting (45 rpm). The results obtained were then compared to measurements performed using the medium pump setting (120 rpm), which is expected to potentially disintegrate unstable oil droplets.

As shown in Figure 2 below, the classic oat milk measured with the slow pump setting displays a bimodal profile, with a minor population peaking at ca 12 µm and a major population peaking between 800 and 1200 µm. This latter population likely represents oil droplets, and their low stability is highlighted by the high variability of the mode, and of the distribution's D_{90} value (see Table 4).

When measured at medium speed, the large particles disappear entirely, as would be expected for instable oil droplets dispersed under high shear conditions. The remaining single peak, with a mode at 12 µm, most likely represents the starch fraction of oat milk.

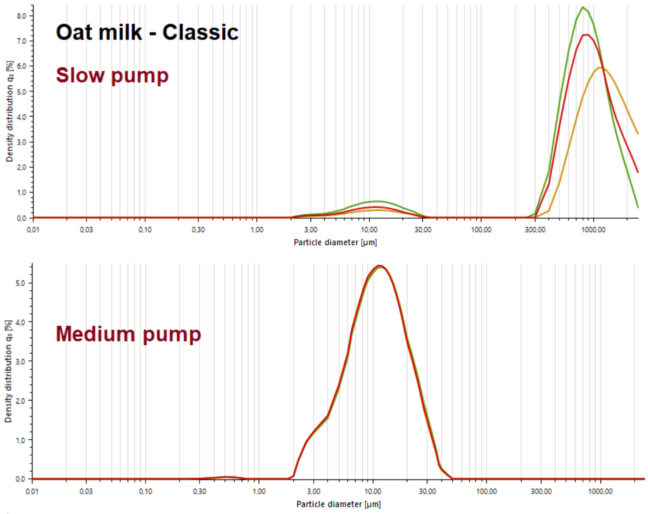

Figure 2: Volume-weighted particle size distribution of the oat milk "classic" sample, measured at slow (45 rpm – upper panel) or medium (120 rpm – lower panel) pumping speed. Overlay of 3 consecutive measurements.

The barista oat milk (see Figure 3 & Table 4) also displays a bimodal profile when measured at slow speed, but the mode of the larger (presumably oil) peak is both significantly smaller (ca 400 µm) and more repeatable than for the classic oat milk. Furthermore, when measured at medium speed, the oil droplet peak is still detectable, although its prominence is reduced compared to the slow speed measurement. This indicates that, although the total fat content of the barista oat milk is roughly double that of classic oat milk, the oil phase is better emulsified, forming smaller droplets that somewhat resist high shear dispersion.

Interestingly, the mode of the starch fraction is also reduced, peaking at ca 4 µm, against 12 µm for the classic oat milk. These observations indicate that the manufacturing of the barista oat milk differs from the classic oat milk in at least two ways. First, the starch fraction appears to have been further hydrolyzed in the barista than in the classic; second, the oil fraction has been emulsified, likely through the addition of dicalcium phosphate (as listed in Table 2).

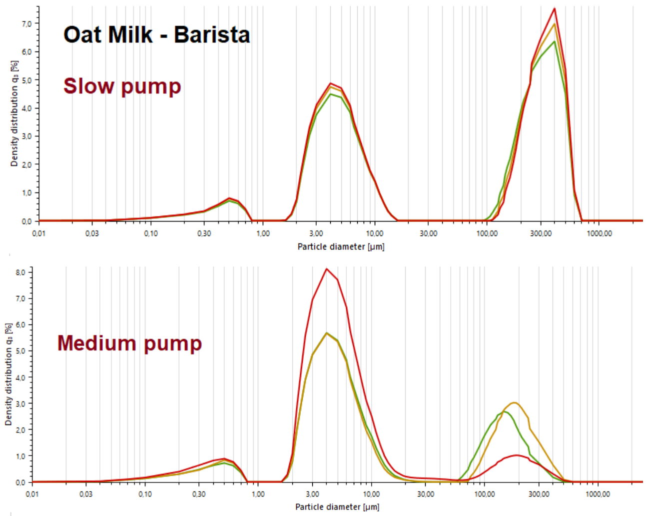

Figure 3: Volume-weighted particle size distribution of the oat milk "barista" sample, measured at slow (45 rpm – upper panel) or medium (120 rpm – lower panel) pumping speed. Overlay of 3 consecutive measurements.

Sample / Pump speed	Mean D_{10} ± STD [µm]	Mean D_{50} ± STD [µm]	Mean D_{90} ± STD [µm]
Classic / slow	409.3 ± 88.4	879.6 ± 163.3	1711 ± 273.7
Classic / medium	4.05 ± 0.03	10.14 ± 0.11	21.59 ± 0.14
Barista / slow	2.36 ± 0.03	11.41 ± 1.0	398.2 ± 4.61
Barista / medium	1.39 ± 0.67	4.71 ± 0.42	122.5 ± 94.4

Table 4: Volume-based results for the oat milk samples.

3.3 Soy Milk Measurements

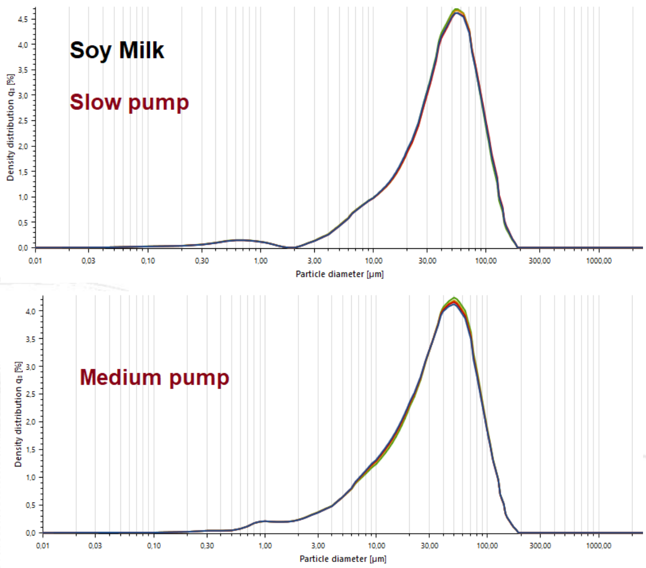

Figure 4: Volume-weighted particle size distribution of the soy milk sample, measured at slow (45 rpm – upper panel) or medium (120 rpm – lower panel) pumping speed. Overlay of 4 consecutive measurements.

Pump speed	Mean D_{10} ± STD [µm]	Mean D_{50} ± STD [µm]	Mean D_{90} ± STD [µm]
Soy / slow	8.43 ± 0.11	40.42 ± 0.27	89.13 ± 0.82
Soy / medium	5.9 ± 0.02	33.38 ± 0.41	80.94 ± 0.24

Table 5: Volume-based results for the soy milk sample

As shown in Figure 4 and Table 5 above, results from soy milk measurements performed using the medium pump speed are only marginally smaller than results obtained using slow pump speed. Strikingly, both particle size distributions are broadly monomodal, with a mode at ca. 50 µm. This correlates well with observations made on dry soy protein concentrate (4), which peaks around 50 to 60 µm. It also suggests that, although soy milk has a relatively high fat content (see Table 2), the lipid fraction is well emulsified and, unlike oat milk, does not form instable oil droplets.

In all, this confirms the excellent colloidal stability of soy milk, as already hinted by the visual observation (Figure 1). As the sample studied here is only composed of water and soy beans, one can speculate that the lecithin naturally contained in the beans acts as emulsifier for the stabilization of the fat fraction.

3.4 Almond Milk Measurements

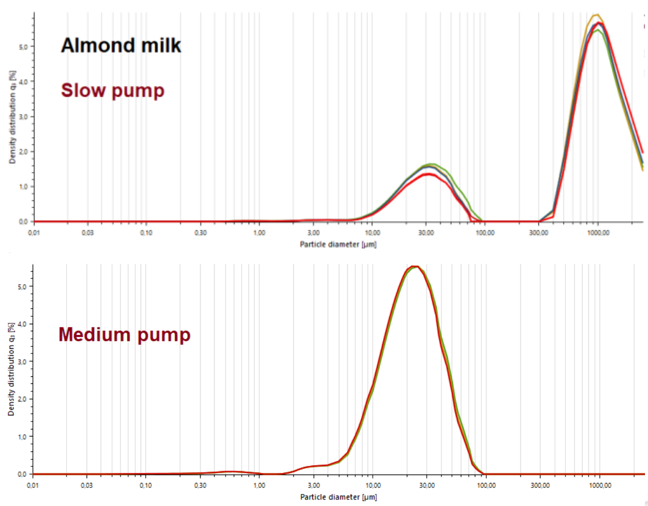

Figure 5: Volume-weighted particle size distribution of the almond milk sample, measured at slow (45 rpm – upper panel) or medium (120 rpm – lower panel) pumping speed. Overlay of consecutive measurements.

Pump speed	Mean D_{10} ± STD [µm]	Mean D_{50} ± STD [µm]	Mean D_{90} ± STD [µm]
Almond / slow	25.53 ± 1.07	814.5 ± 39.91	1722 ± 55.7
Almond / medium	8.66 ± 0.17	20.62 ± 0.41	42.25 ± 0.93

Table 6: Volume-based results for the almond milk sample

Almond milk (Figure 5, Table 6) measured using the slow pump setting displays a bimodal profile, with a large fraction presumably representing oil droplets peaking at ca 1000 µm, and a minor fraction peaking at ca 30 µm.

When measured at medium pump speed, the oil droplet fraction disappears, indicating that the oil phase is unstable. This correlates with the dephasing observed visually (Figure 1). The remaining solid fraction, representing the ground almond particles, peaks at 25 µm.

4 Conclusion

The PSA can characterize the particle size distribution of oat, soy and almond milk. The size of both the solid particles and the oil droplets can be measured, and can highlight differences in manufacturing processes. The PSA can therefore be used to monitor the grinding and filtering processes, but also to assess the colloidal stability of the finished product.

5 References

1. *Reducing food's environmental impacts through producers and consumers.* **Poore, Joseph & Nemecek, Thomas.** 2018, Science, 360:987-992.

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4. **Anton Paar.** *Like Two Peas in a Pod: Combining Powder Rheology and Laser Diffraction for the Analysis of Plant-Based Proteins.* Anton Paar GmbH, 2023. Application report Nb D43IA038EN.

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