

Effect of Whey on the Rheological and Physical Properties of Bread

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Abstract

Whey is discarded in large volumes every year as a by-product of cheesemaking, despite its considerable nutritional value, which raises the question of whether it could be put to better use in food production rather than treated as an environmental pollutant. In this study, the water added during bread dough mixing was replaced with whey at levels of 0%, 25%, 50%, 75% and 100%, and the resulting loaves were evaluated for their physical properties (volume, weight, height, specific volume and Pelshenke fermentation time) alongside the rheological behaviour of the dough as measured by the alveograph. Loaf volume rose steadily from 1340 cm³ in the control to 1410 cm³ at full substitution, and weight increased in parallel from 495.66 g to 509.33 g, with both differences significant at $p \leq 0.05$; height and specific volume, however, were not significantly affected by the substitution level. Pelshenke time increased only slightly with higher whey content, from 130.33 to 132.33 minutes. On the rheological side, dough resistance to deformation (P) and deformation energy (W) improved markedly at full substitution, while extensibility (L) and the swelling index (G) remained fairly stable across treatments, and the P/L balance ratio rose sharply at 100% whey. Correlation analysis showed a very strong positive relationship between volume and weight ($r^2=0.99$) and between W and P ($r^2=0.99$), against a comparatively weak association between L and specific volume ($r^2=0.32$). Taken together, these findings support the use of whey as a partial or full water substitute in breadmaking without compromising the physical and rheological quality of the product, and in several respects even improving it.

Keywords: *Whey; Bread; Rheological properties; Alveograph; Physical properties; Pelshenke test.*

Introduction

The dairy industry generates enormous quantities of whey worldwide as a by-product of cheese manufacture, and a large share of it is still discharged without being put to use, despite its valuable nutrient content and the real environmental burden its disposal creates through its high biochemical oxygen demand (BOD), which can range between 30,000 and 50,000 mg/L.



Whey is generated as the liquid fraction that remains once the cheese curd has been separated, and it occurs in two main types depending on the coagulation method: sweet whey (pH 6.02–6.58) and acid whey (pH 3.57–4.34), with sweet whey accounting for most of the world's production. It consists mainly of lactose, which makes up 70–72% of its total solids, together with 8–10% protein and 12–15% minerals on a dry-matter basis; its biological value as a protein source is considered even higher than that of egg protein, owing to its richness in branched-chain amino acids.

Although bread remains one of the most widely consumed staple foods worldwide, the wheat flour used in its production is deficient in several essential amino acids, particularly lysine, threonine and tryptophan. Whey solids have been shown to help offset this shortcoming: several studies report that they promote crust browning through the Maillard reaction, improve moisture retention and crumb softness, and supply soluble minerals such as calcium, potassium and phosphorus.

On this basis, replacing part or all of the water used in bread dough with whey can be seen as a way of achieving two goals at once: reducing the environmental impact of whey disposal and enhancing the nutritional value of bread. The present study was therefore designed to investigate the effect of replacing water with whey at levels of 0%, 25%, 50%, 75% and 100% on the physical properties of the resulting bread loaf (volume, weight, height, specific volume and Pelshenke fermentation time), as well as on the rheological properties of the dough as measured by the alveograph.

Material and methods

Materials and equipment

Commercial wheat flour (Barima brand) obtained from the Libyan local market, commercial Turkish-made dry yeast, and whey collected from a cheese and dairy-products factory in the Souk El-Sebt area south of Tripoli were used in this study. Whey samples were stored in opaque containers at 4°C until analysis. A 1000 g-capacity dough mixer (Hommer), a laboratory mill (Retsch), a Kjeldahl unit for protein determination (Gerhardt), a Soxhlet unit for fat extraction (Gerhardt), a muffle furnace (Carbolite), a locally fabricated seed-displacement tank for loaf-volume measurement, and an alveograph (Chopin, France) were used for the analyses.

Dough and bread preparation

Bread was prepared by the conventional straight-dough method using 300 g flour, 6 g salt, 7.5 g dry yeast, 18 g sugar, 6 mL oil, and 175 mL water for the control sample. In the treatment



samples, water was progressively replaced with whey at the designated substitution levels (0%, 25%, 50%, 75% and 100%), while all other ingredients were kept constant across treatments. The ingredients were mixed for 5 minutes, and the dough was then left to ferment at 30–32°C until it reached optimum volume. It was subsequently divided, moulded and baked for 23 minutes at 210°C, then left to cool for one hour at room temperature (28–30°C).

Evaluation of physical properties

- Loaf volume was determined by the rapeseed-displacement method according to AACC Method 10-10 (2000).
- Loaf weight was measured by direct weighing of the loaf after cooling.
- Loaf height was measured across the longitudinal section at both edges and the centre, and the mean of the three readings was taken.
- Specific volume was calculated by dividing loaf volume (cm³) by loaf weight (g).
- The Pelshenke test was used to estimate dough fermentation time according to AACC Method 50-56 (2000), by recording the time required for a dough ball immersed in water at 30°C to disintegrate.

Evaluation of rheological properties (alveograph)

The rheological properties of the dough were measured with an Alveograph PC device following AACC Method 54-30.02. The instrument works by injecting air into a thin sheet of dough until a bubble forms that mimics the retention of carbon dioxide during fermentation. The dough was prepared from 250 g flour with a 2.5% sodium chloride solution, mixed for approximately 8 minutes, then divided, sheeted and rested before being inflated with air until rupture. The following parameters were derived from the resulting curve:

- P (dough tenacity, mmH₂O): the maximum pressure required to rupture the dough bubble, indicating dough strength.
- L (extensibility, mm): the length of the curve up to the point of rupture, which is influenced by the amount and quality of gluten.
- P/L: the ratio expressing the balance between dough strength and extensibility.
- W (deformation energy, J×10⁻⁴): the amount of work needed to rupture the bubble, used as an index of the combined strength of flour and dough.
- G (swelling index): the square root of the air volume required for rupture, calculated as $G = 2.22\sqrt{L}$.

Statistical analysis



Data were analysed according to a completely randomized design (CRD) with three replicates per treatment. Two-way analysis of variance (ANOVA) was performed at a probability level of $p \leq 0.05$ using SPSS software, and means were separated using the least significant difference (LSD) test.

Results and discussion

Physical properties of the bread loaf

Table 1 shows that loaf volume increased significantly ($p \leq 0.05$) with increasing whey substitution level. Volume remained close to the control at the 25% level, then rose progressively at 50%, 75% and 100% substitution, reaching 1353.33, 1366.66 and 1410 cm³, respectively, compared with 1340 cm³ for the control. This trend agrees with the increase in loaf volume reported with increasing dried whey powder content, and is consistent with findings observing volume increasing from 1250 to 1433 cm³ with the addition of only 4% whey protein. This increase may be linked to an improved capacity of the dough to retain the carbon dioxide released during fermentation, together with the role of whey protein in binding water and fat during mixing, which enhances water-vapour retention and increases loaf volume during baking.

Loaf weight followed a similar pattern, increasing significantly from 495.66 g in the control to 509.33 g at full substitution (Table 1), consistent with previous findings. This can be attributed to the lactose, protein and ash content of whey and to the water-holding capacity of its proteins, which is reflected in an increase in the final weight of the loaf.

By contrast, neither height nor specific volume showed any significant differences ($p \leq 0.05$) among the substitution levels, in agreement with findings that likewise found replacing water with pasteurized whey at 50% and 100% had no significant effect on specific volume.

Table 1. Effect of whey substitution level on the physical properties of the bread loaf

Whey (%)	Water (%)	Volume (cm ³)	Weight (g)	Height (cm)	Specific volume (cm ³ /g)
0	100	1340.00 d	495.66 d	5.63 a	2.70 a
25	75	1345.00 cd	497.66 d	5.63 a	2.70 a
50	50	1353.33 c	501.00 c	5.66 a	2.70 a
75	25	1366.66 b	505.66 b	5.66 a	2.70 a
100	0	1410.00 a	509.33 a	5.80 a	2.76 a
LSD		11.26	2.73	0.20	0.02

Values followed by the same letter within a column are not significantly different ($p \leq 0.05$).

Pelshenke test (fermentation time)

The Pelshenke test measures the time needed for a dough ball immersed in water to disintegrate, providing an indirect indicator of the strength of the gluten network and its capacity to retain gas during fermentation. Table 2 shows that this time ranged from 130.33 minutes in the control to 132.33 minutes at full substitution, with significant differences occurring only between these two extreme treatments, while the intermediate levels (25%, 50% and 75%) did not differ significantly from one another. This slight increase in disintegration time may be attributed to the role of whey proteins in reinforcing the gluten network, and to their tendency to absorb water, which raises overall dough water absorption and improves gas retention.

Table 2. Effect of whey substitution level on fermentation time (Pelshenke test)

Whey (%)	Water (%)	Pelshenke test (min)
0	100	130.33 b
25	75	130.66 ab
50	50	131.66 ab
75	25	132.00 ab
100	0	132.33 a
LSD		1.693

Values followed by the same letter within a column are not significantly different ($p \leq 0.05$).

Rheological properties of the dough (alveograph)

Dough deformation energy (W) increased from 104 ($\times 10^{-4}$ J) in the control to 122, 124 and 128 ($\times 10^{-4}$ J) at 25%, 50% and 75% substitution, respectively, then rose sharply to 183 ($\times 10^{-4}$ J) at full substitution (Table 3). This increase reflects a strengthening of the gluten network and its positive association with water absorption, since whey proteins contribute to reinforcing and stabilizing this network and enhance the ability of the dough to retain fermentation gases. This finding did not fully match reports recording the highest W value at a 16% substitution level rather than at full substitution, although it agreed in its general direction with observations from trials on low-quality flour.

Similarly, dough resistance to deformation (P) increased markedly with increasing substitution level, from 80 mmH₂O in the control to 118 mmH₂O at full substitution, indicating an improved capacity of the dough to withstand pressure. This can be explained by the milk proteins, fat and lactose in whey, which increase dough stability, a trend that agrees with related findings.

Extensibility (L), on the other hand, rose from 33 mm in the control to 36 mm at the first substitution level, then remained around 35–36 mm across the remaining treatments with no

notable change, indicating that the addition of whey does not weaken dough elasticity but keeps it at an acceptable level, consistent with the general view regarding the relationship between extensibility and final loaf volume. The P/L balance ratio, meanwhile, stayed close to 2.42 at the 0%, 25% and 50% levels, then rose to 2.60 at 75%, and reached its highest value (3.28) at full substitution, reflecting the dough's tendency, at this level in particular, toward greater firmness at the expense of extensibility. The swelling index (G) ranged between 12.8 and 13.3 with no notable differences among treatments, suggesting that the dough's gas-retention capacity remained stable regardless of the substitution level.

Table 3. Effect of whey substitution level on the rheological properties of the dough (alveograph)

Whey (%)	Water (%)	P (mmH ₂ O)	L (mm)	P/L	W (J×10 ⁻⁴)	G
0	100	80	33	2.42	104	12.8
25	75	89	36	2.47	122	13.3
50	50	87	36	2.42	124	13.3
75	25	91	35	2.60	128	13.1
100	0	118	36	3.28	183	13.3

Correlation between physical and rheological properties

Table 4 presents the correlation coefficient (r^2) matrix between substitution level and the set of physical and rheological properties studied. The strongest correlation in the matrix was between loaf volume and loaf weight ($r^2=0.99$), an expected result given that any increase in volume is usually accompanied by a parallel increase in weight. Deformation energy (W) followed the same pattern, correlating with resistance to deformation (P) at a similarly high strength ($r^2=0.99$), and also correlating strongly with height and specific volume (0.97 and 0.94, respectively). The P/L balance ratio likewise showed a strong correlation with most physical properties, particularly volume, specific volume and height (between 0.97 and 0.98).

Conversely, extensibility (L) showed the weakest correlation with most of the other properties: its correlation with specific volume did not exceed $r^2=0.32$, with height it was $r^2=0.42$, and with the P/L ratio $r^2=0.36$, suggesting that dough elasticity does not directly govern these properties to the extent that dough resistance and energy do. A very strong correlation was also observed between the swelling index (G) and extensibility (L) itself ($r^2=0.99$), which is logical given that G is calculated directly from L. Taken together, these relationships highlight that improvements in the rheological properties of whey-enriched dough are directly reflected in the physical properties of the resulting loaf, even though the strength of this influence varies from one property to another.

Table 4. Correlation coefficient (r^2) between substitution level and the physical and rheological properties of the bread loaf

	Substitution	Volume	Specific volume	Height	Weight	P	L	P/L
Volume	0.90	–	–	–	–	–	–	–
Specific volume	0.69	0.92	–	–	–	–	–	–
Height	0.83	0.98	0.96	–	–	–	–	–
Weight	0.99	0.93	0.73	0.86	–	–	–	–
P	0.84	0.97	0.95	0.96	0.85	–	–	–
L	0.60	0.44	0.32	0.42	0.50	0.53	–	–
P/L	0.79	0.97	0.98	0.97	0.83	0.98	0.36	–
W	0.86	0.97	0.94	0.97	0.87	0.99	0.57	0.96
G	0.57	0.43	0.33	0.42	0.47	0.54	0.99	0.36

Values represent the coefficient of determination (r^2) between each pair of variables; a dash (–) indicates that the value is repeated in the corresponding direction of the matrix and is not shown to avoid duplication.

Conclusion

On the basis of the results presented above, replacing water with whey in bread dough did not impair the physical or rheological properties of the product; on the contrary, it improved several of them as the substitution level increased. Loaf volume and weight increased significantly with higher substitution levels, without a comparable effect on height or specific volume, while Pelshenke fermentation time was only slightly prolonged at full substitution relative to the control, reflecting a strengthened gluten network. Dough resistance to deformation (P) and deformation energy (W) improved markedly at the full substitution level, whereas extensibility (L) and the swelling index (G) remained nearly constant across all treatments, and the correlation matrix confirmed a very strong relationship between volume and weight and between W and P, against a much weaker association between L and specific volume.

Taken together, these findings support the adoption of whey as a partial or full substitute for water in breadmaking, an approach that would reduce the environmental impact of this dairy by-product while simultaneously raising the nutritional and quality profile of the final product, offering a practical route for the dairy and baking industries to convert an underused waste stream into a value-adding ingredient.

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