

Original Article

Development and Nutritional, Physical, and Functional Assessment of a Plant-Based Oat-Almond Milk Alternative

Easha Aerken Mustafa¹, Shahzad Muzammil², Muhammad Naveed Babur³

¹ Faculty of Allied Health Sciences, The Superior University, Lahore, Pakistan

² Faculty of Allied Health Sciences, The Superior University, Lahore, Pakistan

³ Professor, Faculty of Allied Health Sciences, The Superior University, Lahore, Pakistan

✉ **Correspondence:** Shahzad Muzammil, shahzad.muzammil@superior.edu.pk

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ABSTRACT

Background: Plant-based milk alternatives are increasingly used by individuals with lactose intolerance, cow-milk allergy, vegan dietary preferences, and interest in plant-based foods. Oat and almond beverages have different nutritional and technological characteristics, and combining them may modify composition, viscosity, physical stability, and sensory acceptance. **Objective:** To formulate oat-almond plant-based beverages at different blending ratios and compare their physicochemical, proximate, short-term physical-stability, and sensory characteristics with single-source oat and almond beverages and cow milk. **Methods:** Six treatments were evaluated: cow milk (T0), 100% oat milk (T01), 100% almond milk (T02), 25% almond/75% oat (T1), 40% almond/60% oat (T2), and 50% almond/50% oat (T3). Moisture, protein, fat, ash, nitrogen-free extract, titratable acidity, pH, viscosity, five-day physical stability, and 9-point hedonic sensory scores were evaluated. Results: LMA and ETT were not relevant to this formulation study. Cow milk had the highest protein (3.30%) and fat (3.90%) levels. Plant-based protein ranged from 1.26% to 1.35%. Corrected NFE values ranged from 4.04% in almond milk to 6.35% in oat milk. T3 had the highest viscosity (10.80 cP) and the highest sensory scores among plant-based treatments, including overall acceptability of 7.45±0.33 compared with 7.80±0.33 for cow milk. T1 showed the least visible separation among blended formulations during the five-day observation. pH did not differ significantly across treatments. **Conclusion:** A 50:50 oat-almond blend provided the strongest sensory performance among the plant-based formulations, whereas the 25:75 almond-oat blend showed better short-term physical stability. The formulations were lower in protein than cow milk and were not micronutrient-fortified; therefore, nutritional equivalence to dairy milk cannot be assumed. **Keywords:** Plant-Based Milk Alternative; Oat Milk; Almond Milk; Sensory Evaluation; Viscosity; Physical Stability; Proximate Composition.

INTRODUCTION

Plant-based milk alternatives have become an important food category in response to lactose intolerance, cow-milk allergy, vegan dietary patterns, changing consumer preferences, and broader interest in plant-derived foods. Their increasing use has stimulated extensive research into formulation, nutrient composition, processing, physical stability, sensory acceptance, and the extent to which these beverages can function as alternatives to conventional dairy products (1–3).

Plant-based beverages are generally produced by extracting soluble and dispersible components from cereals, nuts, legumes, seeds, or other plant materials into an aqueous phase. Depending on the product and intended technological characteristics, production may subsequently involve filtration, homogenization, heat treatment, enzymatic processing, stabilization, flavor modification, or micronutrient fortification. These processing decisions can substantially influence extraction efficiency, particle characteristics, rheology, emulsion stability, flavor, digestibility, and final product quality (1,3). Plant-based beverages are not nutritionally uniform. Protein, carbohydrate, fat, vitamins, minerals, and energy density vary according to the plant source, plant-to-water ratio, formulation, fortification strategy, and manufacturing process. Comparative nutritional studies have demonstrated that many cereal- and nut-based beverages contain substantially less protein than cow milk and may not provide equivalent concentrations of calcium, iodine, vitamin D, vitamin B12, or other micronutrients unless appropriately fortified (4–8). Consequently, sensory or functional similarity to milk does not necessarily imply nutritional equivalence.

Oat beverages are increasingly popular because of their mild cereal flavor, carbohydrate composition, and potential to produce a relatively creamy sensory profile. Their technological characteristics are influenced by oat cultivar, starch and beta-glucan content, particle size, enzymatic treatment, extraction conditions, homogenization, thermal processing, and formulation additives (9–12). Studies using different oat cultivars and processing strategies have demonstrated substantial variation in protein content, physical separation, rheological properties, and sensory characteristics, indicating that oat beverages should be considered formulation-dependent products rather than a nutritionally or technologically uniform category (9–12).

Almond beverages provide a distinct nut-derived sensory profile and generally contain less protein than dairy milk when produced using conventional dilution ratios. Processing methods influence extraction efficiency, moisture, total solids, lipid recovery, protein concentration, ash, flavor, physical stability, and sensory characteristics (13–15). Emerging extraction and processing strategies, including hydrodynamic cavitation and other technologies, have therefore been investigated to improve almond-beverage production and product quality (13). Formulation studies have also demonstrated that botanical additions and processing modifications can materially influence the physicochemical and sensory profile of almond-based beverages (14,15).

Combining oat and almond beverages may offer an opportunity to integrate complementary sensory and technological characteristics. Increasing oat contribution may alter carbohydrate content, suspended solids, mouthfeel, and viscosity, whereas increasing almond contribution may modify lipid content, flavor, appearance, and aroma. However, blended products cannot necessarily be predicted from the characteristics of their individual components because starches, proteins, lipids, fibers, and suspended particles may interact within the dispersed beverage system. Contemporary evidence indicates that blending different plant matrices can modify viscosity, particle behavior, sedimentation, flavor, and sensory perception in ways that differ from single-source products (3,16).

Physical stability is particularly important in plant-based beverages because suspended particles and dispersed lipid phases may undergo sedimentation, aggregation, creaming, or phase separation during storage. Particle size, density differences, interfacial properties, viscosity, homogenization, thermal processing, hydrocolloids, and storage conditions are among the principal factors influencing physical performance (1,3,16,17). Modern processing techniques such as ultrasonication, thermosonication, high-pressure homogenization, and stabilization systems are consequently being investigated to improve beverage homogeneity and storage stability (3,17).

Sensory quality is equally important in product development. A beverage with an acceptable nutritional composition may have limited practical value when flavor, aroma, appearance, texture, or mouthfeel are poorly accepted. Comparative evaluation of commercial plant-based beverages has demonstrated substantial differences in viscosity, particle size, physical stability, aroma compounds, flavor, and mouthfeel between plant sources and cow milk (16). Product development should therefore integrate physicochemical, nutritional, stability, and sensory evaluation rather than optimizing any single domain in isolation.

Recent nutritional evaluations of commercially available plant-based beverages further reinforce the need for careful product positioning. Considerable variation exists between products, and equivalence to cow milk cannot be assumed on the basis of product name or intended use alone (6–8). Contemporary reviews similarly emphasize fortification, processing, nutrient bioavailability, allergenicity, and formulation quality when evaluating plant-based milk alternatives as dietary substitutes (18).

The present laboratory-scale study therefore developed oat, almond, and oat–almond blended beverages at defined ratios and compared them with cow milk. The objective was to evaluate proximate composition, acidity, pH, viscosity, short-term physical stability, and sensory acceptance and to identify promising formulations for further product development.

MATERIALS AND METHODS

A laboratory-scale product-development study was conducted over six months in the Culinary Laboratory of The Superior University, Lahore, Pakistan. Rolled oats, raw almonds, honey, and salt were obtained from markets in Lahore and stored in airtight containers.

For preparation of oat milk, 100 g of rolled oats were soaked in water for two hours and drained. The soaked oats were blended with 400 mL cold water for approximately 30–40 seconds. The resulting slurry was filtered through two layers of muslin cloth using gentle pressure to recover the liquid fraction.

For preparation of almond milk, 100 g of raw almonds were soaked in water for 12 hours, drained, and hulled. The almonds were blended with 400 mL water for two minutes and filtered through two layers of muslin cloth.

Honey and a small quantity of salt were added to the plant-based formulations to improve palatability. The final recipe was selected after preliminary formulation trials.

Six treatments were evaluated. Cow milk served as the dairy control, two treatments consisted of single-source oat or almond milk, and three consisted of different oat–almond blending ratios.

Table 1. Oat–Almond Treatment Plan

Treatment	Almond Milk	Oat Milk
T0 – Cow milk control	–	–
T01 – Oat milk	0%	100%
T02 – Almond milk	100%	0%
T1	25%	75%
T2	40%	60%
T3	50%	50%

Moisture was determined by oven drying at 105°C to constant mass. Protein was determined using the Kjeldahl method with a nitrogen conversion factor of 6.25. Fat was determined by Soxhlet extraction and ash by incineration according to established AOAC laboratory methods (19).

Nitrogen-free extract was calculated as:

$$\text{NFE (\%)} = 100 - [\text{moisture (\%)} + \text{protein (\%)} + \text{fat (\%)} + \text{ash (\%)}].$$

Because the originally calculated NFE values did not consistently equal the difference obtained from their respective moisture, protein, fat, and ash means, NFE was recalculated directly from the reported component means using the stated equation.

Titrateable acidity was determined by titrating 10 mL of sample with sodium hydroxide using phenolphthalein as the indicator. pH was measured using a calibrated pH meter after stabilization of the electrode in each sample.

Viscosity was measured using a Brookfield viscometer with approximately 100 mL of sample placed in a clean beaker, and the results were expressed in centipoise (cP) in accordance with the operating principles of the instrument (20).

Physical stability was observed under refrigeration at days 0, 3, and 5. Color, appearance, aroma, layering, creaming, sedimentation, and visible separation were assessed. These observations represented short-term physical stability rather than microbiological shelf-life testing.

Sensory evaluation assessed color, taste, appearance, mouthfeel, and overall acceptability using a 9-point hedonic scale ranging from 1, “dislike extremely,” to 9, “like extremely.”

Ethical approval was obtained from the Institutional Review Board of Superior University, Lahore, Pakistan.

Data were analyzed using IBM SPSS Statistics version 26. One-way analysis of variance was used for treatment comparisons and the least significant difference test for post-hoc comparisons at a significance level of $p < 0.05$. Results are presented as mean $\pm$ standard deviation, and statistical grouping letters are retained from the analytical results.

RESULTS

The six beverages differed in proximate composition.

Cow milk had the lowest moisture content at $86.8 \pm 0.30\%$ and the highest protein, fat, and ash concentrations at $3.30 \pm 0.20\%$, $3.90 \pm 0.12\%$, and $0.70 \pm 0.03\%$, respectively.

Almond milk had the highest moisture content at $93.0 \pm 0.35\%$ and the lowest plant-based protein value at $1.26 \pm 0.08\%$.

Plant-based protein concentrations were substantially lower than those of cow milk, ranging from 1.26% to 1.35%.

The initially calculated NFE values did not consistently agree with the stated calculation by difference. Recalculated values were 5.30% for T0, 6.35% for T01, 4.04% for T02, 5.71% for T1, 5.46% for T2, and 5.18% for T3.

Table 2. Proximate Composition of Cow Milk and Plant-Based Treatments

Treatment	Moisture, %	Protein, %	Fat, %	Ash, %	Corrected NFE, %
T0	86.8 ± 0.30	3.30 ± 0.20	3.90 ± 0.12	0.70 ± 0.03	5.30
T01	90.4 ± 0.40	1.35 ± 0.10	1.50 ± 0.07	0.40 ± 0.02	6.35
T02	93.0 ± 0.35	1.26 ± 0.08	1.20 ± 0.06	0.50 ± 0.04	4.04
T1	91.1 ± 0.25	1.33 ± 0.09	1.43 ± 0.05	0.43 ± 0.01	5.71
T2	91.4 ± 0.28	1.31 ± 0.07	1.38 ± 0.04	0.45 ± 0.02	5.46
T3	91.7 ± 0.30	1.31 ± 0.10	1.35 ± 0.04	0.46 ± 0.05	5.18

Titrate acidity was greatest in cow milk at $0.145 \pm 0.004\%$ and lowest in almond milk at $0.050 \pm 0.002\%$. The plant-based blends had intermediate values. pH varied only from 6.68 ± 0.01 to 6.82 ± 0.02 , and all six treatments shared the same statistical grouping, indicating no statistically significant pH difference. Viscosity differed substantially. Almond milk had the lowest viscosity at 2.10 ± 0.10 cP. T3, the 50:50 blend, had the highest viscosity at 10.80 ± 0.30 cP, exceeding the 7.50 ± 0.25 cP measured for cow milk.

Table 3. Acidity, pH, and Viscosity

Treatment	Titrate Acidity, %	pH	Viscosity, cP
T0	0.145 ± 0.004	6.82 ± 0.02	7.50 ± 0.25
T01	0.070 ± 0.003	6.79 ± 0.03	6.00 ± 0.20
T02	0.050 ± 0.002	6.68 ± 0.01	2.10 ± 0.10
T1	0.065 ± 0.001	6.76 ± 0.04	5.03 ± 0.15
T2	0.062 ± 0.021	6.74 ± 0.01	4.05 ± 0.12
T3	0.060 ± 0.022	6.73 ± 0.05	10.80 ± 0.30

Short-term physical stability varied across formulations. All treatments were initially visually acceptable. By day 3, mild changes were observed in some single-source and blended beverages. T1 showed the least visible change among blended treatments. By day 5, T3 demonstrated the most obvious separation among the blends, while T1 remained comparatively uniform.

Table 4. Short-Term Physical Stability During Refrigerated Observation

Treatment	Day 0	Day 3	Day 5
T0	Acceptable appearance; no visible layering/creaming	Minimal visible change	Comparatively stable appearance
T01	Uniform	Slight dullness	Continued visual change
T02	Uniform	Slight yellowing; light creaming/sedimentation	Visible settling; mild graininess
T1	Uniform	Least visible change among blends	Generally uniform; slight settling
T2	Uniform	Minor change	Mild dullness and sedimentation
T3	Uniform	Early creaming and faint odor	Dullness, particle settling, layering and separation

Table 5. Sensory Evaluation Using the 9-Point Hedonic Scale

Treatment	Color	Taste	Appearance	Mouthfeel	Overall Acceptability
T0	7.54 ± 0.26^a	7.71 ± 0.30^a	7.71 ± 0.35^a	7.54 ± 0.32^a	7.80 ± 0.33^a
T01	5.70 ± 0.26^c	4.91 ± 0.30^c	5.61 ± 0.35^c	4.91 ± 0.32^c	4.99 ± 0.33^c
T02	6.57 ± 0.26^b	5.70 ± 0.30^b	6.57 ± 0.35^b	5.61 ± 0.32^b	5.78 ± 0.33^b
T1	6.31 ± 0.26^b	5.70 ± 0.30^b	5.87 ± 0.35^{bc}	5.78 ± 0.32^b	5.78 ± 0.33^b
T2	6.92 ± 0.26^{ab}	6.22 ± 0.30^b	6.75 ± 0.35^b	6.40 ± 0.32^{ab}	6.57 ± 0.33^{ab}
T3	7.45 ± 0.26^a	7.27 ± 0.30^a	7.45 ± 0.35^a	7.36 ± 0.32^a	7.45 ± 0.33^a

Values sharing one or more superscript letters within an attribute were not statistically different in the post-hoc analysis.

Sensory scores were highest for cow milk overall, but T3 approached the dairy control and was the strongest-performing plant-based formulation. Cow milk had an overall acceptability score of 7.80 ± 0.33 , while T3 scored 7.45 ± 0.33 . Both treatments were assigned the same statistical grouping in the post-hoc analysis. T3 also had the highest plant-based scores for color, taste, appearance, and mouthfeel. Oat milk alone had the lowest overall acceptability score at 4.99 ± 0.33 .

DISCUSSION

The present study demonstrates that blending oat and almond beverages alters nutritional composition, viscosity, short-term physical stability, and sensory performance. No single formulation was optimal across every evaluated domain. Cow milk retained the highest protein and fat concentrations, T3 produced the strongest sensory performance and greatest viscosity among the plant-based formulations, whereas T1 showed the most favorable visual stability among the blended beverages during the five-day observation period.

Cow milk contained 3.30% protein compared with approximately 1.26–1.35% among the oat, almond, and blended beverages. This difference is consistent with nutritional evaluations showing that many cereal- and nut-based milk alternatives contain considerably less protein than cow milk, although the magnitude of the difference varies according to product formulation, fortification, and plant source (4–8,16). These findings emphasize that similarity in appearance or culinary use should not be interpreted as evidence of nutritional interchangeability.

The nutritional distinction is particularly important when plant-based beverages are consumed frequently or replace dairy products in diets where protein or micronutrient intake is marginal. Commercial products vary considerably in calcium, iodine, vitamin B12, vitamin D, and other nutrients, and fortification practices differ between manufacturers and markets (6–8,18). Evaluation of plant-based beverages should therefore consider total dietary contribution and nutrient composition in addition to sensory similarity.

The plant-based formulations also contained less fat than cow milk under the present preparation conditions. Oat milk contained 1.50% fat, almond milk 1.20%, and the blends approximately 1.35–1.43%. These values should be interpreted as properties of the specific extraction procedures used in this study rather than fixed characteristics of oat or almond beverages. Plant-to-water ratio, extraction efficiency, filtration, particle retention, homogenization, ingredient addition, and thermal or mechanical processing can substantially influence final composition (1,3,9,10,13).

Correction of the NFE values was necessary because the original calculated values were inconsistent with the explicitly stated calculation by difference. After recalculation, oat milk had the highest estimated NFE among the plant-based formulations at 6.35%, whereas almond milk had the lowest at 4.04%. The blended formulations lay between these single-source beverages, with NFE declining from 5.71% in T1 to 5.18% in T3 as the almond contribution increased.

Oat beverages are influenced by starch, beta-glucan, other soluble and insoluble carbohydrates, and processing conditions, all of which can modify solids behavior and rheological characteristics (9–12). Variation between oat cultivars and processing strategies has previously been associated with differences in composition, physical stability, and sensory quality (9–12). The present findings similarly demonstrate that relatively small changes in formulation can coincide with substantial differences in beverage viscosity.

Viscosity showed one of the clearest formulation effects. Almond milk had the lowest viscosity, while the 50:50 T3 blend had the highest viscosity of all treatments, including cow milk. This non-linear pattern indicates that viscosity was not simply proportional to the amount of oat beverage in the formulation. Interactions among dispersed oat and almond solids may have altered the structure of the beverage system. Contemporary research shows that particle dimensions, macromolecular interactions, lipid droplets, total solids, processing conditions, and the structure of the continuous phase can collectively influence viscosity and mouthfeel in plant-based beverages (1,3,16,17). Because particle size, beta-glucan concentration, lipid-droplet characteristics, and microstructure were not measured in the present study, a specific mechanism for the high T3 viscosity cannot be established.

The short-term stability findings demonstrate an important distinction between apparent viscosity and storage stability. T3 had the greatest viscosity and strongest sensory acceptance among the plant-based formulations but showed relatively prominent layering and settling by day 5. In contrast, T1 had lower sensory scores and lower viscosity but retained the most uniform appearance among the blended

treatments. Sedimentation and creaming are influenced not only by bulk viscosity but also by particle size, density differences, aggregation, interfacial properties, homogenization, and the structure of the continuous and dispersed phases (1,3,16,17). Consequently, increasing viscosity alone cannot be assumed to prevent physical separation.

The five-day assessment should be interpreted specifically as an evaluation of visible physical stability. No microbiological testing was performed, and acceptable visual appearance or organoleptic characteristics cannot establish microbiological safety or commercial shelf life. Plant-based dairy alternatives can present distinct microbiological and chemical food-safety considerations, making microbiological validation an important component of future shelf-life assessment (21). Processing reviews similarly distinguish physicochemical stability from microbial preservation and emphasize the need to evaluate both when commercial storage claims are intended (17).

Sensory evaluation identified T3 as the strongest plant-based formulation. Its scores for color, taste, appearance, mouthfeel, and overall acceptability approached those of cow milk, with T3 and cow milk sharing statistical groupings for several attributes. These findings are compatible with recent comparative research demonstrating that ingredient selection, particle characteristics, viscosity, volatile compounds, and macronutrient composition contribute substantially to the sensory differences observed among cow milk, oat milk, almond milk, and blended plant-based beverages (16).

The improvement observed with the 50:50 formulation suggests that combining oat and almond components may provide complementary sensory properties under the preparation conditions used. Evidence from plant-based beverage research increasingly supports matrix blending and targeted formulation as approaches to balance texture, flavor, nutritional characteristics, and physical performance (3,16). However, sensory improvement in one formulation cannot be assumed to transfer directly to other oat cultivars, almond concentrations, extraction ratios, sweetener levels, or processing conditions.

T01, the oat-only beverage, had the lowest overall acceptability score, whereas T02 almond milk and T1 received moderate scores. T2 showed an intermediate sensory profile and T3 performed substantially better. Previous oat- and almond-beverage studies have similarly demonstrated that plant source, processing conditions, added ingredients, flavor profile, viscosity, and physical stability influence sensory responses (9,12–17). These findings reinforce the need to optimize nutritional, sensory, and physicochemical properties concurrently rather than assuming that improvement in one characteristic will necessarily improve overall acceptance.

The sensory findings should nevertheless not be generalized directly to population-wide consumer preference. The study involved a limited sensory evaluation rather than a large representative consumer survey, and the exact panel size and participant characteristics were not reported. Furthermore, if the same panelists evaluated all six formulations, the data would have a repeated-measures structure. Under such circumstances, an analysis assuming complete independence between treatment observations would not fully account for within-panel correlation. Future sensory investigations should therefore report panel composition and employ statistical methods appropriate to the experimental structure.

The absence of micronutrient analysis represents another important limitation. Calcium, vitamin D, vitamin B12, iodine, riboflavin, and other micronutrients can materially affect whether a plant-based beverage can function as a nutritional substitute for dairy milk (4–8,18). Commercial plant-based products frequently use fortification because their unfortified nutrient profiles differ from those of cow milk (6–8,18). The present formulations were not micronutrient-fortified, and nutritional equivalence to cow milk therefore cannot be inferred.

The study also did not evaluate beta-glucan concentration, amino-acid composition and quality, fatty-acid composition, digestibility, antioxidant compounds, or nutrient bioavailability. Such measurements would provide a more complete nutritional characterization, particularly because processing can alter extraction, molecular structure, digestibility, and the bioaccessibility of nutrients and phytochemicals in plant-based beverages (3,10–12,15,18).

Processing conditions are central to the performance of both oat- and almond-based beverages. Oat pretreatment, enzyme activity, filtration, homogenization, heat treatment, particle-size reduction, and almond extraction conditions can modify nutrient recovery, rheology, mouthfeel, phase separation, and sensory characteristics (3,9–17). The relatively simple soaking, blending, and muslin-filtration procedures used in the current study have the advantage of laboratory practicality but differ substantially from industrial manufacturing processes.

Industrial-scale plant-based beverages may incorporate homogenization, enzymatic treatment, stabilizers, hydrocolloids, ultrasonication, thermal processing, aseptic packaging, or other technologies to improve uniformity, shelf stability, nutritional functionality, and sensory consistency (1,3,17,18). The present experiment should therefore be interpreted as a laboratory prototype-development study rather than validation of a commercially optimized beverage.

Among the formulations tested, T3 appears most promising for further sensory-focused development, whereas T1 warrants continued evaluation as a stability-oriented formulation. Future formulation experiments could investigate whether the favorable sensory characteristics of T3 can be retained while reducing separation through optimized homogenization, particle-size control, stabilization, or processing. Similar technological approaches have been explored across contemporary plant-based beverage systems to improve suspension stability without unacceptable deterioration of sensory quality (3,12,17).

Further work should also investigate protein enrichment and micronutrient fortification to improve nutritional value while monitoring possible effects on viscosity, flavor, mouthfeel, physical stability, and consumer acceptance. Because formulation changes can simultaneously influence nutritional and technological properties, optimization should be undertaken using integrated nutritional, physicochemical, microbiological, and sensory endpoints rather than treating these outcomes independently (3,18).

CONCLUSION

Oat, almond, and blended oat-almond plant-based beverages were successfully developed and compared with cow milk.

Cow milk had substantially higher protein, fat, and ash concentrations than the plant-based formulations. Oat milk had the highest corrected NFE value among the plant-based products, whereas almond milk had the highest moisture content and lowest viscosity.

The 50:50 oat-almond blend, T3, produced the highest viscosity and strongest sensory performance among the plant-based formulations, with overall acceptability statistically grouped with cow milk in the post-hoc analysis.

The 25% almond/75% oat formulation, T1, displayed the most favorable short-term physical stability among the blended treatments during five days of refrigerated observation.

These findings support further development of oat-almond beverages but do not establish nutritional equivalence to cow milk, microbiological safety, or commercial shelf stability. Additional fortification, stabilization, microbiological testing, comprehensive nutrient analysis, consumer testing, and longer storage studies are required before broader nutritional or commercial conclusions can be made.

LIMITATIONS

The experiment was conducted at laboratory scale and did not reproduce industrial processing conditions.

The exact quantity of honey added to each formulation was not reported sufficiently to ensure complete formulation reproducibility.

The number and characteristics of sensory panelists were not reported.

The statistical analysis of sensory scores may not have accounted for repeated ratings if the same individuals evaluated all treatments.

The study did not include microbiological safety or spoilage testing.

Physical storage observations were limited to five days.

Calcium, vitamin D, vitamin B12, iodine, and other micronutrients were not measured.

The formulations were not micronutrient-fortified.

Beta-glucan, amino-acid quality, fatty-acid composition, nutrient bioavailability, and digestibility were not evaluated.

Commercial packaging, preservation systems, cost, allergen-management procedures, and scale-up feasibility were not studied.

RECOMMENDATIONS

T3 should be prioritized for further sensory-focused optimization because it demonstrated the highest acceptability among the plant-based formulations.

T1 should be evaluated as a stability-oriented comparator because it displayed less visible separation during short-term refrigerated observation.

Further formulation work should assess homogenization, stabilizers, processing conditions, and particle-size control to reduce settling and creaming.

Complete nutritional characterization should include micronutrients, amino-acid quality, beta-glucan, fatty-acid composition, digestibility, and nutrient bioavailability.

If the product is intended to substitute routinely for cow milk, appropriate micronutrient fortification should be investigated rather than assuming natural nutritional equivalence.

Future sensory studies should report panel size, demographic characteristics, blinding, sample randomization, palate-cleansing procedures, repeated-measures structure, and statistical methods appropriate to the experimental design.

Microbiological, storage, water-activity, and shelf-life studies should be completed before claims regarding storage safety or commercialization are made.

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