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ORIGINAL RESEARCH ARTICLE

Calcium and vitamin D3 fortification of almond milk: A chemical engineering approach to enhancing nutritional quality and mineral bioavailability

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ABSTRACT

Background: The increasing demand for plant-based dairy alternatives has highlighted almond milk as a popular option due to its favorable sensory properties and suitability for individuals with lactose intolerance or milk protein sensitivity. However, its inherently low levels of calcium and vitamin D3 limit its nutritional equivalence to cow's milk, particularly in populations with higher mineral requirements. Aim: This study aimed to enhance the nutritional and functional quality of almond milk through calcium and vitamin D3 fortification, while evaluating its physicochemical characteristics, mineral bioavailability, and sensory acceptability. Methods: Almond milk was prepared using an almond-to-water ratio of 1:4, followed by fortification with calcium chloride (0.3 g/100 mL) and vitamin D3 (80 IU/100 mL). Physicochemical properties were analyzed using standard methods, while calcium bioavailability was assessed using an in vitro digestion model based on the INFOGEST protocol. Mineral quantification was performed using atomic absorption spectrophotometry. Sensory evaluation was conducted to assess product acceptability. Results: Fortification significantly increased calcium content from 13.99 to 120 mg/100 mL without altering macronutrient composition. Physicochemical parameters such as density, electrical conductivity, and total salts increased, indicating effective dissolution and homogeneous distribution of the added minerals. In vitro digestion revealed progressive calcium release, with bioavailability reaching 65.41% during the intestinal phase. Sensory evaluation demonstrated high acceptability, with no adverse effects on flavor, texture, or appearance. Conclusion: Calcium and vitamin D3 fortification effectively improves the nutritional profile and functional performance of almond milk. The integration of food science and chemical engineering principles enables the development of a stable, bioavailable, and consumer-acceptable plant-based beverage, supporting its potential as a viable alternative to dairy milk.

Keywords: almond milk; calcium fortification; vitamin D3; plant-based milk alternative; bioavailability; INFOGEST

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1. Introduction

In recent years, the global food sector has experienced a marked shift toward functional foods and plant-based dairy alternatives, driven by evolving consumer demands for health-conscious, allergen-free, and environmentally sustainable products[1-3]. This transition reflects not only dietary considerations—such as lactose intolerance, milk protein allergies, and vegan preferences—but also broader concerns related to sustainability and resource-efficient food production[4]. Within this context, almond milk, as shown in **Figure 1**, has emerged as one of the most widely consumed plant-based beverages due to its favorable sensory attributes, low caloric content, and richness in unsaturated fatty acids and vitamin E[5].

From a compositional standpoint, however, almond milk differs substantially from conventional cow's milk. While it offers several health and dietary advantages, it remains nutritionally limited, particularly in terms of calcium and vitamin D content[4]. These micronutrients play a critical role in human health: calcium is essential for bone mineralization and structural integrity, whereas vitamin D3 facilitates intestinal calcium absorption and regulates systemic calcium homeostasis. Consequently, the substitution of dairy milk with unfortified almond milk may lead to nutritional insufficiencies, especially among vulnerable populations such as children, adolescents, and the elderly[5]. This limitation underscores the importance of targeted food fortification strategies to enhance the nutritional profile of plant-based beverages.

Plant-based milk alternatives are typically produced through the aqueous extraction of plant materials, including nuts, legumes, cereals, and oilseeds. Although these products mimic the appearance of dairy milk, their physicochemical composition and nutritional value are inherently different[6,7]. Almond milk, derived from *Prunus dulcis* (**Figure 1**), is particularly valued for being free of lactose, cholesterol, and casein, making it suitable for individuals with dairy-related intolerances or sensitivities[8]. Nevertheless, the extraction process—often involving soaking, grinding, and filtration—results in only partial transfer of nutrients from raw almonds to the final beverage. As a result, unfortified almond milk generally contains lower levels of protein, minerals, and fat-soluble vitamins compared with its dairy counterpart[9,10].

Figure 1. Appearance of laboratory-prepared almond milk and unripe fruits of *Prunus dulcis.*

From a chemical engineering perspective, the production and fortification of almond milk involve several critical unit operations, including mass transfer during extraction, particle size reduction, solid–liquid separation, and homogenization. These processes influence not only nutrient retention but also the stability and consistency of the final product. For instance, inefficient extraction kinetics or suboptimal solid–liquid ratios may limit the transfer of proteins and minerals, while inadequate homogenization can lead to phase separation and reduced product stability. Therefore, optimizing processing parameters is essential for improving both nutritional yield and product quality at an industrial scale.

Food fortification, defined as the deliberate addition of essential micronutrients to improve nutritional value, represents a practical and widely adopted approach to address these deficiencies[11]. Calcium, the most abundant mineral in the human body, is vital for skeletal health, while vitamin D acts synergistically by enhancing calcium absorption in the gastrointestinal tract. However, in plant-based matrices, the bioavailability of calcium may be compromised by antinutritional factors such as phytic acid, which can chelate minerals and reduce their absorption[12]. Co-fortification with vitamin D is therefore particularly advantageous in overcoming these limitations and improving overall nutrient utilization[13].

Despite its nutritional benefits, fortification introduces several physicochemical and engineering challenges. The incorporation of calcium salts can significantly influence parameters such as pH, ionic strength, density, and electrical conductivity, potentially affecting product stability. Furthermore, inadequate dispersion of mineral additives may lead to sedimentation, aggregation, or undesirable textural properties, such as a gritty mouthfeel[14]. From a process engineering standpoint, achieving uniform dispersion requires careful control of mixing dynamics, particle size distribution, and colloidal stability, often through advanced techniques such as high-pressure homogenization or emulsification[15]. Accordingly, the successful development of fortified almond milk must balance nutritional enhancement with physicochemical stability and sensory acceptability. This necessitates an integrated approach that combines principles of food science and chemical engineering to optimize formulation, processing conditions, and product performance[16].

2. Research problem and objectives

The increasing reliance on plant-based milk alternatives, particularly almond milk, has raised important nutritional concerns. Although almond milk provides several health and dietary advantages—such as the absence of lactose, cholesterol, and allergenic milk proteins—its use as a direct substitute for dairy milk may result in insufficient intake of critical micronutrients, notably calcium and vitamin D. These deficiencies are especially concerning in vulnerable populations, including young children aged 2 – 5 years, where adequate mineral intake is essential for proper skeletal development and long-term health[17].

From both a nutritional and process engineering perspective, as shown in **Figure 2**, this limitation highlights the need for effective fortification strategies that not only enhance micronutrient content but also ensure their stability, dispersion, and bioavailability within the beverage matrix. In plant-based systems, the incorporation of mineral salts and fat-soluble vitamins presents challenges related to mass transfer, solubility, colloidal stability, and phase behavior, which must be carefully controlled during processing[18]. Accordingly, this study aims to evaluate almond milk as a functional alternative for individuals with lactose intolerance or milk protein sensitivity, while addressing its inherent nutritional limitations through calcium and vitamin D3 fortification. Specifically, the objectives are to: (i) improve the nutritional profile of almond milk to better approximate that of dairy milk; (ii) assess the physicochemical properties and in vitro bioavailability of the added micronutrients; and (iii) optimize product formulation and processing conditions, from a chemical engineering standpoint, to achieve a stable, homogeneous, and sensorially acceptable fortified beverage.

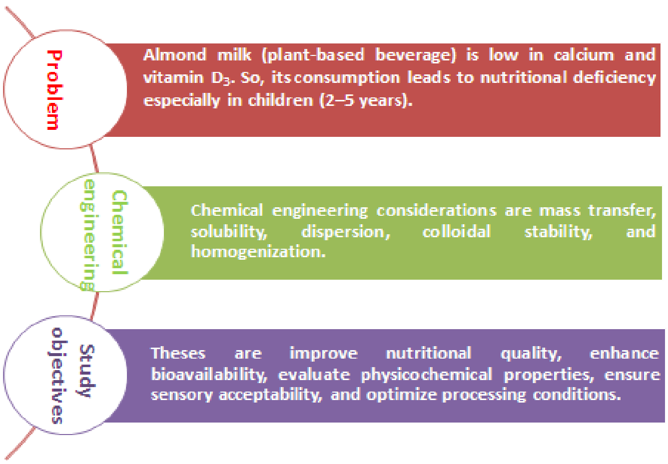

Figure 2. Conceptual framework for calcium and vitamin D_3 fortification of almond milk from a nutritional and chemical engineering perspective.

3. Materials and Methods

3.1. Materials

Raw almonds obtained from *Prunus dulcis*, sterilized water, calcium chloride, and liquid vitamin D_3 (cholecalciferol) were used as the primary ingredients for almond milk preparation and fortification. Analytical-grade reagents, including nitric acid, deionized water, and certified calcium standard solutions, were employed for mineral analysis. For the *in vitro* digestion experiments, reagents simulating gastrointestinal conditions were utilized, including sodium chloride, pepsin, hydrochloric acid, potassium dihydrogen phosphate, sodium hydroxide, and bile salts.

3.2. Equipments

The experimental work was conducted using standard laboratory and analytical instruments, including a milk analyzer for compositional analysis, an incubator for controlled digestion conditions, a high-speed blender for size reduction and extraction, and a calibrated pH meter. Additional equipment included an analytical balance, atomic absorption spectrophotometer for calcium quantification, muffle furnace for dry ashing, centrifuge for phase separation, hot plate for digestion processes, and volumetric glassware for precise solution preparation. From a chemical engineering perspective, these tools supported key operations such as particle size reduction, solid–liquid extraction, phase separation, thermal processing, and analytical quantification, all of which are critical for ensuring process reproducibility and data reliability.

3.3. Preparation and fortification of almond milk

Almond milk was prepared following a controlled extraction protocol. Briefly, 225 g of raw almonds were soaked in water overnight to facilitate hydration and softening. The hydrated almonds were manually dehulled and subsequently blended with sterilized water to promote solid–liquid extraction of soluble components, including lipids, proteins, and micronutrients. The resulting slurry was filtered to remove insoluble residues, yielding a uniform aqueous extract, which was then pasteurized to ensure microbiological safety. Fortification was carried out at room temperature by adding 0.3 g of calcium chloride and one drop of liquid vitamin D_3 (equivalent to 80 IU) per 100 mL of almond milk. From a process engineering standpoint, this step required effective mixing and mass transfer to achieve homogeneous dispersion of the fortificants and prevent localized supersaturation or precipitation.

3.4. In vitro digestion and calcium bioavailability

The fortified samples were subjected to a static *in vitro* digestion model based on the standardized INFOGEST protocol to simulate gastrointestinal conditions[19]. This method allows for the assessment of nutrient release and potential bioavailability under controlled pH and enzymatic environments. Calcium availability was quantified using atomic absorption spectrophotometry following sample preparation steps that included centrifugation for phase separation, dry ashing in a muffle furnace to remove organic matter, and subsequent wet digestion using nitric acid[20]. These procedures ensured accurate determination of mineral content by converting all calcium forms into measurable ionic species. From a chemical engineering viewpoint, this analytical workflow reflects principles of phase separation, thermal decomposition, and mass transfer, which are essential for isolating and quantifying target analytes in complex food matrices.

3.5. Sensory evaluation of almond milk

The sensory quality of almond milk samples was evaluated to understand their overall acceptability from a consumer perspective. A panel of 10–15 semi-trained participants, familiar with basic sensory assessment, was recruited for this purpose. All samples were prepared under identical conditions and served fresh at a chilled temperature (approximately 8–10 °C) to ensure consistency. To avoid bias, each sample was placed in identical disposable cups and labeled with random three-digit codes. The order of presentation was randomized for each panelist. Participants were asked to assess key sensory attributes, including color, aroma, taste, mouthfeel, and overall acceptability.

A 10-point hedonic scale was used, where a score of 1 indicated “dislike extremely” and 10 indicated “like extremely.” Panelists evaluated each sample independently and recorded their impressions. Drinking water was provided between samples to help cleanse the palate and reduce any carryover effects. The evaluation was conducted in a quiet, well-lit setting to minimize distractions and allow panelists to focus on their perceptions. After data collection, the scores for each attribute were compiled and expressed as mean ± standard deviation. Statistical analysis was then applied to identify any significant differences among the samples. This approach provided a balanced and realistic assessment of the sensory characteristics of the almond milk samples.

4. Results and Discussion

The fortification of almond milk with calcium and vitamin D_3 resulted in a substantial improvement in its nutritional profile, particularly in terms of mineral content and functional performance. The observed increase in calcium concentration from 13.99 to 120 mg/100 mL confirms the efficiency of the fortification strategy and brings the product closer to the mineral levels typically found in dairy milk[21]. Similar enhancements have been reported in fortified plant-based beverages, where calcium salts such as calcium chloride or calcium carbonate significantly elevate mineral content without markedly altering macronutrient composition[22]. The stability of fat, protein, and sugar levels in the present study is consistent with previous findings indicating that mineral fortification primarily influences the ionic environment rather than organic constituents[23]. The observed increases in density and electrical conductivity further support the successful dissolution and dispersion of calcium ions within the system[24]. From a chemical engineering standpoint, these results emphasize the importance of mass transfer efficiency, mixing intensity, and solute–solvent interactions in achieving a homogeneous fortified matrix, particularly in colloidal food systems.

The *in vitro* digestion results demonstrated a progressive and sustained release of calcium, with bioavailability reaching 65.41% during the intestinal phase. This release pattern aligns with previous studies reporting that highly soluble calcium salts exhibit improved bioaccessibility compared to less soluble forms, particularly under dynamic pH conditions of the gastrointestinal tract[25]. Moreover, the inclusion of vitamin D_3 likely contributed to enhanced calcium utilization by facilitating intestinal absorption and reducing the likelihood of insoluble complex formation with plant-derived antinutritional factors such as phytic acid[26] (**Figure 3**). Comparable studies on fortified soy and oat beverages have similarly highlighted the role of vitamin D_3 in improving mineral uptake and functional efficacy[27-29].

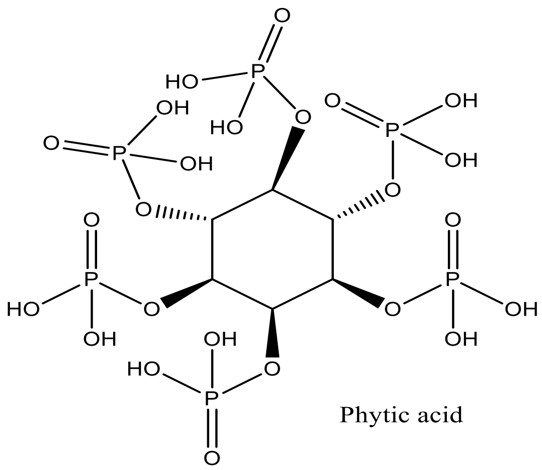

Figure 3. The chemical framework of phytic acid.

From an engineering perspective, the digestion process can be interpreted through transport phenomena and dissolution kinetics, where pH-driven solubility changes and diffusion gradients govern the release and availability of ionic calcium[30]. Importantly, the high sensory scores observed for the fortified product indicate that the applied formulation and processing conditions successfully balanced nutritional enhancement with consumer acceptability[31]. This outcome is consistent with prior reports emphasizing that optimized fortification must consider not only compositional targets but also rheological behavior, colloidal stability, and particle dispersion, which are critical determinants of texture and mouthfeel in plant-based beverages.

4.1. Physicochemical characteristics of the control sample

The physicochemical characterization of the control (unfortified) almond milk provides an essential baseline for evaluating the impact of subsequent fortification. As presented in **Table 1**, the control sample exhibited relatively low concentrations of protein (1.1%), fat (2.4%), and minerals, which is consistent with the dilution effect associated with the applied extraction ratio and the inherent limitations of aqueous extraction processes. The solids-not-fat content (3.2%) and total sugars (1.7%) further reflect the partial transfer of soluble constituents from raw almonds into the aqueous phase, indicating that a significant fraction of nutrients remains in the residual solid matrix after filtration.

From a physicochemical perspective, the low salt content (0.2%) and electrical conductivity (3.0) observed in the control sample represent the natural ionic baseline of unfortified almond milk. These parameters are particularly important, as they influence not only the nutritional value but also the stability and functional behavior of the beverage[32]. The measured density (10.5) and freezing point (−0.194 C) are indicative of a relatively dilute system, primarily composed of water (62.6%), with dispersed macromolecules and emulsified lipids. From a chemical engineering standpoint, these findings highlight the role of solid – liquid extraction efficiency, mass transfer limitations, and phase separation processes in determining the final composition of plant-based milk alternatives. In particular, the relatively low protein and mineral content suggests that the extraction and homogenization steps may not fully optimize the recovery of intracellular components, emphasizing the importance of process optimization in improving yield and functional quality. Overall, the control sample demonstrates that, while almond milk possesses favorable sensory and compositional attributes, it remains nutritionally limited in its unfortified form. This baseline characterization underscores the necessity of fortification and provides a critical reference point for assessing improvements in mineral content, physicochemical properties, and bioavailability in fortified formulations[33].

Table 1. Compositional and physicochemical characteristics of the control almond milk sample.

Parameter	Control value
Fat (%)	2.4
Solids-not-fat, SNF (%)	3.2
Density (g/cm^3)	10.5
Protein (%)	1.1
Total sugars (%)	1.7
Salts (%)	0.2
Added water (%)	62.6
Freezing point (°C)	-0.194
Conductivity	3.0

4.2. Comparison before and after fortification

The comparative analysis between control and fortified almond milk samples demonstrates that the fortification strategy effectively enhanced mineral content and modified key physicochemical properties without adversely affecting the primary organic constituents. As shown in **Table 2**, the concentrations of fat, protein, and total sugars remained unchanged after fortification, indicating that the addition of calcium chloride and vitamin D_3 did not disrupt the intrinsic macronutrient composition of the almond milk matrix.

This stability is particularly important, as it suggests that fortification can be achieved without compromising the nutritional balance or sensory integrity associated with these components.

In contrast, significant increases were observed in mineral-related parameters. Calcium content increased markedly from 13.99 to 120 mg/100 mL, while total salts rose from 0.2% to 0.6%, confirming the successful incorporation of the fortificants. These changes were accompanied by increases in density and electrical conductivity, reflecting the higher ionic strength and total dissolved solids in the fortified system[34]. From a physicochemical standpoint, these results indicate efficient dissolution of calcium chloride and its uniform distribution throughout the liquid phase. The slight decrease in freezing point further supports the presence of additional solutes, which influence colligative properties of the system[35].

From a chemical engineering perspective, the observed improvements can be attributed to effective mixing, mass transfer, and dispersion processes during fortification. The homogeneous distribution of calcium ions suggests that the system achieved a stable colloidal state, minimizing the risk of precipitation or phase separation. This is critical in plant-based beverages, where improper incorporation of mineral salts can lead to instability, sedimentation, or undesirable textural changes. The slight increase in solids-not-fat content also reflects the contribution of added micronutrients to the overall solid fraction of the beverage[36]. Overall, the data confirm that the selected fortification approach successfully enhances the nutritional value of almond milk while maintaining its physicochemical stability. This balance between enrichment and system stability highlights the importance of integrating food science principles with chemical engineering considerations, particularly in optimizing solute incorporation and maintaining product homogeneity in complex liquid food systems.

Table 2. Effect of calcium and vitamin D_3 fortification on the composition of almond milk.

Parameter	Control	Fortified
Fat (%)	2.4	2.4
Protein (%)	1.1	1.1
Total sugars (%)	1.7	1.7
Salts (%)	0.2	0.6
Calcium (mg/100 mL)	13.99	120
Vitamin D3	Absent	2 µg
Solids-not-fat (%)	3.2	3.6
Density (g/cm^3)	10.5	11.2
Conductivity	3.0	4.1
Freezing point (°C)	-0.194	-0.215

4.3. Calcium release during the gastric phase

The results of the simulated gastric digestion phase demonstrate a gradual and time-dependent increase in calcium release from the fortified almond milk. As shown in **Table 3**, no measurable calcium absorption was detected at the initial time point; however, absorption increased to 4.0% after 2 hours and further to 7.67% after 4 hours. This progressive release pattern reflects the influence of the acidic gastric environment (pH ≈ 2), which enhances the solubility of calcium chloride and promotes the dissociation of calcium ions into the surrounding medium. The constant total calcium concentration throughout the experiment indicates that the observed changes are due to redistribution between bound and bioaccessible forms rather than loss of calcium from the system.

From a mechanistic perspective, the increase in absorbed calcium can be attributed to the acid-driven dissolution kinetics of calcium salts and the disruption of weak interactions between calcium ions and plant-derived macromolecules, such as proteins and phytates[37]. The acidic conditions facilitate protonation of binding sites, thereby reducing their affinity for calcium and enhancing its release into the soluble fraction[38]. However, the relatively modest absorption percentages observed during the gastric phase suggest that calcium mobilization is still limited at this stage, with a substantial portion remaining associated with the food matrix[39].

From a chemical engineering standpoint, these findings can be interpreted in terms of mass transfer and diffusion processes, where the rate of calcium release is governed by the transport of ions from the solid–liquid interface into the bulk solution. The gradual increase in bioaccessible calcium reflects a system approaching equilibrium under dynamic conditions, influenced by pH, ionic strength, and mixing. These results highlight the importance of considering dissolution kinetics, interfacial transport, and phase interactions when designing fortified food systems aimed at maximizing nutrient bioavailability. Overall, the gastric phase serves as a critical initial step in calcium liberation, setting the stage for further release and absorption under intestinal conditions. The observed behavior confirms that the selected calcium source is responsive to physiological conditions and capable of providing bioaccessible calcium in a controlled and progressive manner.

Table 3. Time-dependent calcium bioavailability in the gastric phase of *in vitro* digestion.

Time (hour)	Total calcium (mg/100 mL)	Released calcium (mg/100 mL)	Absorption (%)
0	120.00	0.00	0
2	120.00	4.80	4.00
4	120.00	9.20	7.67

4.4. Calcium availability during the intestinal phase

The intestinal phase of the *in vitro* digestion model revealed a pronounced and sustained increase in calcium availability over time, indicating efficient release and potential absorption under near-physiological conditions. As shown in **Table 4**, the proportion of absorbed calcium increased progressively from 7.67% at the initial time point to 65.41% after 12 hours. This steady rise demonstrates that a substantial fraction of calcium initially associated with the almond milk matrix becomes bioaccessible during intestinal digestion. Unlike the gastric phase, where calcium release was relatively limited, the intestinal environment (pH $\approx$ 7–7.5) promotes conditions that favor continued solubilization and transport of calcium ions.

Mechanistically, the enhanced availability can be attributed to several interacting factors. The relatively high solubility of calcium chloride facilitates sustained release, while the presence of vitamin D_3 likely contributes indirectly by promoting calcium uptake mechanisms and reducing precipitation losses[40]. In addition, the buffering capacity of the intestinal medium and the presence of bile salts may improve the dispersion of lipid-associated components, thereby facilitating the release of calcium bound within the food matrix. Although plant-derived antinutritional factors can limit mineral bioavailability, the progressive increase observed suggests that their inhibitory effects are partially overcome under intestinal conditions[41].

From a chemical engineering perspective, the observed behavior reflects the interplay of transport phenomena, dissolution kinetics, and phase equilibrium in a dynamic multiphase system. The gradual increase in absorbed calcium can be interpreted as a diffusion-controlled process, where calcium ions migrate from the bulk matrix into the aqueous phase under concentration gradients. The system approaches a quasi-equilibrium state over time, governed by solubility limits, ionic interactions, and mixing efficiency[42]. These findings underscore the importance of designing fortified food systems with consideration of mass transfer efficiency, solute stability, and interaction with the surrounding matrix, as these factors directly influence nutrient bioavailability. Overall, the intestinal phase results confirm that the selected fortification strategy not only increases total calcium content but also ensures its effective release and availability under simulated physiological conditions[43]. This highlights the functional value of the fortified almond milk as a nutritionally enhanced beverage capable of delivering bioaccessible calcium in a controlled and sustained manner[44].

Table 4. Calcium bioavailability profile of fortified almond milk during intestinal digestion.

Time (hour)	Total calcium (mg/100 mL)	Absorbed calcium (mg/100 mL)	Absorption (%)
0	120.00	9.20	7.67
2	120.00	25.40	21.16
4	120.00	42.00	35.00
6	120.00	55.20	46.00
8	120.00	66.30	55.25
10	120.00	72.80	60.66
12	120.00	78.50	65.41

4.5. Sensory evaluation

The sensory evaluation results indicate that calcium and vitamin D3 fortification did not compromise, and may have even enhanced, the overall acceptability of almond milk. As presented in **Table 5**, the fortified product achieved high scores across all evaluated attributes, including color (9.5), flavor (9.0), texture (8.8), aroma (9.2), and overall acceptability (9.1). These findings suggest that the fortification process was successfully implemented without introducing undesirable sensory defects, such as bitterness, chalkiness, or phase separation, which are commonly associated with mineral-enriched beverages.

From a sensory and physicochemical standpoint, the improved color and visual appearance may be attributed to the uniform dispersion of calcium salts, which can enhance light scattering and impart a more appealing whiteness, thereby mimicking the appearance of dairy milk[45]. The high flavor and aroma scores indicate that the added fortificants did not negatively interact with the inherent flavor profile of almond milk, preserving its characteristic mild and pleasant taste. Furthermore, the smooth texture and absence of grittiness suggest effective control over particle size distribution and colloidal stability, preventing sedimentation or aggregation of mineral particles.

From a chemical engineering perspective, these results highlight the importance of optimizing mixing efficiency, homogenization, and dispersion mechanisms during fortification[46]. Proper control of these unit operations ensures that the added micronutrients are evenly distributed within the liquid matrix, minimizing localized concentration gradients that could otherwise lead to sensory defects[47]. Additionally, maintaining a stable emulsion system is critical for preserving mouthfeel and consistency, particularly in plant-based beverages that inherently possess complex multiphase structures[48]. Overall, the sensory data confirm that the fortified almond milk meets consumer expectations in terms of quality and palatability, demonstrating that nutritional enhancement can be achieved without sacrificing sensory performance[49]. This balance between functional improvement and consumer acceptability is essential for the successful development and market adoption of fortified plant-based beverages[50,51].

Table 5. Sensory attributes and acceptability scores of fortified almond milk.

Sensory attribute	Score (out of 10) mean ± standard deviation	Descriptive rating
Color	9.5 ± 1.02	White
Flavor	9.0 ± 1.17	Almond flavor
Texture	8.8 ± 0.98	Smooth and homogeneous

Aroma	9.2 ± 0.88	Pleasant and acceptable
Overall acceptability	9.1 ± 1.15	Highly acceptable

5. Recommendations and future directions

The findings of this study demonstrate the feasibility of enhancing the nutritional quality of almond milk through calcium and vitamin D_3 fortification while maintaining desirable physicochemical and sensory properties. However, several aspects warrant further investigation to support the translation of this formulation from laboratory scale to industrial application. Future studies should evaluate the long-term storage stability of the fortified product under different environmental conditions, including temperature fluctuations and light exposure, as these factors may influence the integrity of vitamin D_3 and the stability of dispersed calcium salts. In addition, extended shelf-life studies are needed to assess potential changes in colloidal stability, sedimentation behavior, and sensory attributes over time. From a nutritional perspective, further research should explore multi-micronutrient fortification strategies, incorporating additional essential nutrients such as iron, zinc, and vitamin B_{12} to better approximate the comprehensive nutritional profile of dairy milk. Given the presence of antinutritional compounds in plant-based matrices, it is also recommended to investigate processing techniques aimed at reducing phytate content, such as enzymatic treatment or fermentation, to further enhance mineral bioavailability. Moreover, *in vivo* studies and clinical trials are necessary to validate the physiological relevance of the *in vitro* digestion results and to confirm the effectiveness of the fortified beverage in improving calcium status in target populations.

From a chemical engineering standpoint, scaling up the fortification process requires optimization of unit operations such as mixing, homogenization, and thermal treatment to ensure consistent product quality. Advanced processing technologies, including high-pressure homogenization, microencapsulation, and nanoemulsion systems, may be explored to improve the stability and bioavailability of both calcium and vitamin D_3. Additionally, process modeling and simulation approaches could be employed to better understand mass transfer dynamics, particle interactions, and phase behavior within the fortified system, thereby enabling more efficient and controlled production at an industrial scale. Finally, future work should expand the application of the proposed fortification approach to other plant-based beverages, such as oat, soy, and rice milk, to evaluate its versatility and broader applicability. Consumer studies involving larger and more diverse populations are also recommended to assess market acceptance and preferences. Collectively, these directions could contribute to the development of next-generation functional plant-based beverages that combine improved nutritional value, technological robustness, and high consumer acceptability.

6. Conclusion

This study demonstrates that calcium and vitamin D_3 fortification is an effective strategy for enhancing the nutritional quality of almond milk, transforming it from a nutritionally limited plant-based beverage into a more functional alternative comparable, in part, to dairy milk. The fortification process significantly increased calcium content while preserving the intrinsic macronutrient composition and maintaining desirable physicochemical properties. The observed increases in density, electrical conductivity, and total salts confirm the successful dissolution and homogeneous distribution of the added fortificants, reflecting efficient process control during formulation. The *in vitro* digestion results further indicate that the fortified system supports progressive and sustained calcium release under simulated gastrointestinal conditions, with substantial bioavailability achieved during the intestinal phase. This behavior highlights the suitability of calcium chloride as a highly soluble mineral source and underscores the complementary role of vitamin D_3 in facilitating calcium utilization. Importantly, the kinetic profile of calcium release suggests that the fortified matrix enables controlled nutrient delivery, governed by pH-dependent solubility and mass transfer processes.

From a chemical engineering perspective, the study emphasizes the critical role of mixing, mass transfer, dispersion, and phase stability in achieving a uniform and stable fortified product. The ability to incorporate micronutrients without inducing sedimentation, phase separation, or undesirable textural changes demonstrates that appropriate control of processing parameters can effectively balance nutritional enhancement with product stability. In addition to its improved nutritional performance, the fortified almond milk exhibited high sensory acceptability, indicating that fortification did not compromise consumer-relevant attributes such as flavor, texture, and appearance. This finding is particularly important for the practical application and market adoption of fortified plant-based beverages. Overall, the results confirm that a carefully designed fortification approach—integrating principles of food science and chemical engineering—can produce a nutritionally enhanced, stable, and palatable almond milk product. These outcomes support the broader potential of fortified plant-based beverages as viable contributors to dietary nutrient intake, particularly in populations with limited access to or preference against dairy products.

Conflict of interest

The authors declare no conflict of interest.

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