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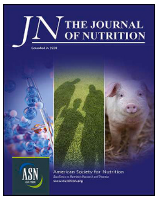

Critical Review

Protein Supplements and Protein-Containing Product Use in Ice Cream: A Review

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ABSTRACT

The increasing demand for high-protein diets, driven by health-conscious consumers and global nutritional challenges, has sparked interest in fortifying popular food products such as ice cream with protein ingredients. Ice cream, a widely consumed dessert, typically offers limited nutritional value, particularly in protein content. This review provides a comprehensive overview of protein supplementation in ice cream production, focusing on functional and technological effects of conventional and emerging protein sources. The article critically evaluates milk-derived proteins, as well as underexplored alternatives including plant-based, microbial, insect-derived, and aquatic proteins. It also addresses legislative constraints, sensory and textural challenges, and formulation strategies for optimizing product quality and consumer acceptance. The integration of proteins into ice cream not only enhances its nutritional profile but also offers potential for market innovation aligned with sustainability and health trends. However, the successful incorporation of these ingredients into ice cream systems requires navigating complex challenges related to formulation performance, sensory quality, regulatory compliance, and consumer acceptance. Functional variability, sensory trade-offs, and limited industrial validation continue to hinder mainstream adoption, especially for novel protein sources. Future advances will depend on a deeper mechanistic understanding of protein behavior in multiphase frozen matrices, as well as the development of formulation strategies that reconcile nutritional value with sensory appeal.

Keywords: protein, ice cream, functional ingredients, alternative proteins, food innovation

Introduction

Global protein deficiency remains a significant nutritional concern, with the FAO reporting that ~1 billion people were affected by insufficient protein intake as of 2020, particularly of animal origin [1]. This situation has been exacerbated by global events such as the COVID-19 pandemic, which disrupted meat, dairy, and aquaculture supply chains [2–4]. Consequently, the demand for protein-fortified foods has intensified, prompting research into alternative delivery formats that combine consumer appeal with nutritional functionality.

Ice cream, despite being one of the most widely consumed desserts worldwide, is often criticized for its limited nutritional profile. Conventional formulations are typically high in sugar and fat while providing only modest amounts of protein [5]. However, growing consumer interest in functional and protein-enriched foods has led to increased scientific and industrial attention on the development of high-protein ice cream products [6,7].

From a technological standpoint, ice cream is a complex, multiphase system, simultaneously a foam, emulsion, and suspension, which is highly sensitive to structural and compositional changes throughout processing and storage [8]. Proteins play a critical role in stabilizing this structure and can enhance textural attributes, overrun, and melting resistance [9]. In addition to their functional benefits, proteins can improve the nutritional value and broaden the marketability of ice cream products, especially when derived from sustainable or novel sources.

Although dairy proteins, particularly those derived from milk and whey, remain the predominant sources in protein-fortified frozen desserts, a growing body of literature is exploring the potential of proteins from plant, microbial, aquatic, and insect origins [10]. These alternatives offer not only environmental and economic benefits but also diverse techno-functional properties

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Abbreviations: EU, European Union; GRAS, generally recognized as safe.

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[11]. However, integrating these proteins into ice cream formulations presents multiple challenges, including sensory acceptability, legal constraints, and process compatibility [12].

This review aims to systematically evaluate and compare the current scientific knowledge on the application of protein ingredients in ice cream production. Special emphasis is placed on the functional, technological, and sensory implications of various protein sources. By critically analyzing recent advances and identifying research gaps, this review offers a foundation for innovation in the development of nutritionally enhanced and consumer-acceptable ice cream products.

This review was prepared as a narrative analysis of scientific and technical sources addressing protein fortification in ice cream. Relevant literature was collected from databases including Scopus, PubMed, Web of Science, and Google Scholar, covering publications from 2010 to 2025. Search keywords included “ice cream,” “protein fortification,” “alternative protein,” “plant protein,” “microbial protein,” “insect protein,” and “precision fermentation.” Only peer-reviewed journal articles, reviews, and book chapters in English were considered. Studies focusing exclusively on nonfrozen dairy systems were excluded. This approach ensured inclusion of the most relevant, recent, and scientifically credible data while maintaining the narrative nature of the review.

Protein Concentrates and Their Prospects in Ice Cream Formulations

Classification and sources of proteins

Protein ingredients used in ice cream formulations can be derived from animal, plant, microbial, and alternative sources. Traditional dairy proteins dominate the industry due to their high biological value, emulsifying and foaming properties, and compatibility with dairy systems. However, alternative proteins are gaining momentum owing to sustainability, consumer trends (vegan, allergen-free diets), and functional diversification (Table 1) [13–17].

Animal-derived proteins include milk proteins (caseins, whey), egg proteins, collagen, and aquatic sources (fish, mollusks). Plant proteins, including soy, pea, rice, hemp, and nuts, are valued for their environmental benefits and functional potential. Microbial proteins (single-cell proteins from yeast or bacteria) and insect-based proteins represent emerging options with promising efficiency and amino acid profiles, although sensory and safety concerns remain. Increasingly, researchers and manufacturers turn to protein blends (animal–plant or plant–plant) to balance amino acid profiles and optimize functional performance (water-binding capacity, overrun, thermal stability) in complex food matrices like ice cream.

Protein production methods

The extraction and processing methods used to obtain protein concentrates or isolates significantly affect their technological properties. Table 2 [18–20] summarizes the major production approaches, their benefits, and limitations.

These technologies enable the tailoring of protein functionality for specific ice cream types, such as low-fat, probiotic, or lactose-free varieties. For example, enzymatically hydrolyzed whey protein offers rapid digestibility and reduced allergenicity, making it suitable for medical or pediatric nutrition applications [21].

TABLE 1
Classification of protein ingredients used in ice cream technology [13–17].

Source	Examples	Key functional properties	Prospects in ice cream
Animal-derived	Milk proteins (casein, whey), egg proteins, collagen, fish proteins	High emulsification, foaming, gelation, good amino acid profile	Widely used, excellent functionality, familiar sensory properties
Plant-derived	Soy, pea, rice, hemp, pumpkin, watermelon seed, amaranth	Water- and fat-binding, emulsifying, structure-forming	Growing popularity, sustainable, may require sensory masking
Microbial	Yeast proteins (e.g., *Candida spp.*), bacterial, mycoprotein	High protein yield, foaming, bioactive potential	Underutilized in ice cream, costly, limited consumer acceptance
Insect-derived	Cricket, grasshopper, mealworm, black soldier fly, silkworm pupae	High protein density, sustainable production	Novel, requires regulatory approval and sensory adaptation
Aquatic	Fish protein concentrate, oyster purée	Rich in essential amino acids, minerals, bioactive peptides	Sensory instability during storage, novel applications in Asia
Blended (hybrid)	Animal–plant mixes, animal–insect, or plant–microbial	Balanced amino acid profile, customizable texture & function	High potential for tailored formulations, requires compatibility optimization

TABLE 2
Overview of protein production methods and their characteristics [18–20].

Method	Description	Advantages	Limitations
Mechanical	Mixing, homogenization, or drying without structural modification	Low-cost, simple integration into mixes	Limited effect on functional properties
Physical	Membrane filtration, heat treatment, spray drying	Enhances solubility, shelf life, particle uniformity	May denature sensitive proteins, energy-intensive
Chemical	Precipitation using acids/alkalis or salts (e.g., caseinates)	Improves emulsifying, foaming, and moisture-binding capacity	Risk of off-flavors or residual chemicals
Biological	Enzymatic hydrolysis into peptides or amino acids	Increases digestibility, bioactivity, produces hypoallergenic forms	Higher cost; may alter sensory quality (e.g., bitterness)
Hybrid/Integrated	Combination of multiple methods (filtration, hydrolysis, drying)	Customizable functionality, supports specialized applications	Requires advanced equipment and process control

Trends and innovation opportunities

The protein-fortified ice cream segment is experiencing rapid growth, especially in North America and Europe, where consumers increasingly seek functional, high-protein snacks [22]. Industry trends include:

1) Integration of plant-based and insect-derived proteins to meet sustainability targets [23].
2) Formulation of hybrid dairy–plant systems for improved texture and amino acid completeness [24].
3) Reduction of sugar and fat alongside protein fortification, supported by regulatory shifts [e.g., European Union (EU) Regulation 1924/2006].

Despite increasing interest, mainstream adoption of novel protein-enriched ice creams is limited by sensory challenges, regulatory variability, and cost [25]. Furthermore, many studies remain at the pilot scale or are geographically constrained. Continued innovation requires interdisciplinary efforts, combining food science, consumer research, nutrition, and food policy.

Protein Concentrates of Animal Origin in Ice Cream Technology

Animal-derived proteins remain the most extensively studied and commercially applied group of protein ingredients in ice cream production [26]. Their high nutritional value, excellent functional properties, and well-established regulatory status make them essential for both traditional and modern formulations. However, despite their widespread use, each category presents unique technological benefits and limitations that warrant careful evaluation. This section provides a comprehensive and critical overview of milk-based, egg-based, collagen, and aquatic protein ingredients in ice cream, along with an analysis of their comparative potential and implementation challenges.

Milk-derived proteins

Milk proteins, particularly caseins and whey proteins, are among the most functional food proteins, widely applied in ice cream production due to their superior emulsifying, foaming, water-binding, and gelation properties. Their incorporation improves overrun, texture, thermal stability, and melt resistance. However, different milk protein ingredients present distinct advantages and limitations, which must be carefully considered when designing ice cream formulations.

Table 3 [21,27–45] provides a comparative overview of commonly used milk protein ingredients, highlighting their functional roles, technological trade-offs, and potential applications in ice cream.

Among dairy-derived proteins, whey-based ingredients offer superior solubility and foaming capacity compared to caseinates, yet their excessive use may compromise air incorporation and lead to undesirable hardness. Casein-rich ingredients, in turn, provide better thermal stability and structure retention, which is advantageous for high-temperature processing but can impart chalky or bitter notes at high inclusion levels.

Despite the technological advantages of isolates and hydrolysates, their higher production costs and potential flavor drawbacks limit widespread industrial adoption. Furthermore, inconsistencies across studies in evaluating melting resistance and overrun indicate a need for standardized assessment protocols. Overall, milk proteins remain the benchmark for functional performance in ice cream, but optimizing their concentration and interactions with stabilizers remains a key research gap.

Egg and collagen-based proteins

Egg white protein concentrates and hydrolysates have been recognized for their remarkable foaming capacity and bioactive properties, including antioxidant potential [46]. Despite these advantages, their inherently limited water-holding capacity constrains their standalone application in ice cream systems, often necessitating coformulation with stabilizers or polysaccharides. Although these proteins may provide functional benefits in dairy-free or medically targeted frozen desserts, empirical evidence on their behavior in conventional ice cream matrices remains scarce [46,47]. Collagen and gelatin, conversely, contribute significantly to gelation and structural integrity, particularly in reduced-fat or sugar-reduced formulations, helping to preserve texture that might otherwise deteriorate during freezing and storage. Nevertheless, their incomplete essential amino acid profile and the potential for off-flavors or undesirable melting characteristics require careful

TABLE 3
Functional characteristics of milk protein ingredients in ice cream technology.

Ingredient	Technological role	Limitations	References
Skimmed/whole milk powder	Improves overrun, flavor; low cost	Moderate solubility; less bioactive content	[27,28]
Whey powder	Stabilizes low-fat ice cream; probiotic-friendly	High lactose; may cause texture defects	[29,30]
Buttermilk powder	Enhances overrun; mimics butter flavor	Understudied in ice cream applications	[31]
Demineralized whey powder	Reduces salt content; improves solubility	May impair probiotic viability	[32,33]
Whey protein concentrate	Enhances viscosity, foaming	Overuse may reduce overrun, affect color	[34,35]
Whey protein isolate	High purity; improves microstructure, stability	At >4% may decrease overrun and increase hardness	[36,37]
Whey protein hydrolysate	Hypoallergenic; fast digestibility	High cost; potential bitterness	[21,38]
Microparticulated whey	Mimics fat; improves texture, melt resistance	Requires controlled particle size	[25,39]
Caseinates/micellar casein	Gelling; enhances stability	Taste defects at high doses	[40,41]
Milk protein concentrate	Increases viscosity; reduces need for stabilizers	May decrease melting resistance	[42,43]
Condensed milk/whey/buttermilk	Enriches solids; supports flavor development	May affect overrun depending on concentration	[44,45]

optimization, typically through blending with other protein sources or flavor-masking strategies [48]. Overall, although egg and collagen-based proteins offer unique functional and nutritional properties, their broader application is tempered by technological constraints, cost considerations, and sensory acceptability.

Aquatic proteins

Marine-derived protein concentrates represent a promising alternative due to their high content of essential amino acids and bioactive peptides. Pilot-scale trials utilizing fish protein hydrolysates indicate satisfactory performance in terms of freeze–thaw stability and protein enrichment [15]. However, the practical incorporation of these proteins into mainstream ice cream is hindered by lipid oxidation, flavor deterioration during storage, and unfamiliar sensory attributes in many consumer markets [49–51]. Emerging strategies, such as the use of cryoprotectants, flavor-masking agents, and encapsulation technologies, are being investigated to mitigate these challenges [52]. Although aquatic proteins demonstrate potential for functional or therapeutic frozen desserts, particularly in markets with higher consumer acceptance of marine flavors, their integration remains limited by processing complexity, cost, and regulatory considerations.

Comparative evaluation and implementation challenges

The selection of animal-derived proteins for ice cream production requires a careful balance among technological feasibility, sensory quality, nutritional contribution, and economic considerations. Milk-derived proteins continue to serve as the industrial benchmark, owing to their multifunctional properties, including emulsification, foaming, gelling, and the provision of a complete amino acid profile. Nevertheless, excessive use of isolates or hydrolysates can compromise texture and flavor, with higher concentrations often resulting in reduced overrun or increased hardness [37,53]. Egg and collagen proteins offer complementary functional advantages, such as enhanced foaming and gelation, yet their broader adoption is limited by lower water-binding capacity, potential off-flavors, and cost constraints. Similarly, aquatic proteins provide high bioactive value and amino acid quality but are constrained by sensory unfamiliarity, oxidative instability, and limited regulatory harmonization, rendering them more suitable for niche or therapeutic products rather than mainstream ice cream formulations [46,50].

Table 4 synthesizes the comparative performance of these protein sources, emphasizing their relative technological and sensory implications, nutritional contribution, and market applicability.

In conclusion, milk proteins remain the most practical and reliable solution for large-scale industrial ice cream production, whereas egg, collagen, and aquatic proteins offer strategic advantages in niche markets. Future innovation is likely to rely on hybrid formulations, cost-efficient processing strategies, and optimized sensory masking to fully exploit the potential of diverse animal protein sources. The integration of these alternative proteins necessitates rigorous validation under large-scale processing conditions to ensure consistent quality, consumer acceptance, and regulatory compliance.

Plant-Based Proteins in Ice Cream Technology

Growing consumer demand for sustainable, health-oriented, and allergen-free food products has accelerated the adoption of plant-based proteins in frozen dessert formulations [22]. Plant proteins not only offer environmental and ethical advantages but also provide considerable functional potential in ice cream matrices. However, their integration is associated with notable sensory, structural, and technological challenges. This section provides a critical appraisal of the functionality, formulation strategies, and limitations of plant-derived protein ingredients in ice cream.

Technological and functional properties

Plant-derived proteins are obtained mainly from leguminous crops (soy, pea, lentil), cereals (rice, oat), oilseeds (hemp, sunflower), and pseudocereals (amaranth, quinoa) (Table 5) [7,54,55].

Plant proteins exhibit distinct functional behavior compared to milk-derived ones. Their lower solubility and emulsifying capacity necessitate the use of hydrocolloids, enzymes, or fat mimetics to achieve similar stability [14,16,56]. Amino acid profiles are often incomplete, requiring complementary protein sources to ensure nutritional adequacy [57].

Soy and pea proteins are the most technically feasible due to their processing maturity and global availability, but they also pose sensory and allergenic constraints, limiting use in certain markets. Rice and hemp proteins, though more neutral in flavor and hypoallergenic, offer poorer emulsification and foam stability, constraining overrun and texture performance.

Modification techniques such as enzymatic hydrolysis or fermentation can improve solubility and mask off-flavors, but these processes increase production costs and may compromise thermal stability, underscoring a trade-off between functionality and economic viability.

TABLE 4
Comparative evaluation of animal-derived protein ingredients for ice cream: technological, sensory, nutritional, and market aspects.

Protein type	Technological feasibility	Sensory impact	Nutritional contribution	Cost	Market applicability
Milk	High	Good	Complete amino acids	Medium	Industrial/mainstream
Egg	Medium	Moderate	Bioactive	High	Dairy-free, medical desserts
Collagen/gelatin	Medium	Moderate	Limited amino acids	Medium	Reduced-fat, functional desserts
Aquatic	Low	Unfamiliar	High bioactivity	High	Niche, therapeutic, regional

"Cost" refers to the relative industrial cost of the protein ingredient, with "Low" indicating widely available and inexpensive ingredients, "Medium" representing moderate-cost ingredients requiring some specialized processing, and "High" indicating expensive or niche ingredients with limited availability or higher production costs.

TABLE 5
Functional features of selected plant-based proteins for ice cream applications.

Protein source	Notable functional properties	Formulation challenges	Examples of application
Soy	High solubility, good emulsification	Beany flavor, allergenicity	High-protein vegan ice creams [7]
Pea	Mild taste, stable foaming	Low solubility; may affect mouthfeel	Plant-based ice cream [54]
Rice	Hypoallergenic, bland flavor, low viscosity	Weak emulsifying capacity	Applied in hypoallergenic/low-fat formulations [55]
Hemp	Balanced amino acid profile	Need a special pretreatment	No data
Pumpkin seed	High digestibility, antioxidant properties	Less studied in frozen matrices	No data
Watermelon seed	Moderate emulsifying and foaming	Limited research; requires taste masking	Used in hybrid protein blends

Functional comparisons are based on published data at laboratory or pilot scale. "Formulation Challenges" reflect sensory and process limitations relevant to industrial ice cream production.

Formulation strategies and innovations

Recent innovations favor hybrid formulations combining multiple plant proteins (e.g., pea–rice or soy–oat) or costructuring them with hydrocolloids, prebiotics, or plant fats [58,59]. Such strategies balance nutritional and sensory properties while mitigating textural defects [17].

Microstructural analyses reveal that plant proteins integrate differently with fat and air phases, often leading to denser and harder textures but enhanced melting resistance [60]. Adjustments through fat-structuring agents or cryoprotectants can optimize these attributes.

Emerging technologies—ultrafiltration, high-moisture extrusion, and precision fermentation—enable tailored protein design with improved emulsification, flavor-binding, and heat stability [61]. However, their scalability, cost-efficiency, and regulatory clarity remain key constraints for industrial adoption.

Sensory and regulatory considerations

Plant-based proteins often introduce bitterness, astringency, or vegetal notes, particularly in isolates or hydrolysates. Approaches such as fermentation or natural flavor masking improve sensory acceptance [62,63].

From a regulatory viewpoint, most plant proteins are generally recognized as safe (GRAS)-listed or approved under EU Novel Food Regulations, yet concerns persist regarding soy and lupin allergenicity, digestibility variability, and lack of compositional standards for plant-based ice cream. These factors hinder cross-market harmonization and complicate labeling.

Research gaps and future directions

Plant-based proteins, including soy, pea, and oat, have emerged as promising ingredients for ice cream formulations due to their sustainability profile, compatibility with vegan product development, and reduced allergenicity. Functional performance can be further enhanced through enzymatic or fermentation-based modifications, improving solubility and sensory attributes. Nevertheless, considerable variability exists among plant species and extraction methods, and evidence regarding long-term storage stability, consumer acceptance, and flavor optimization remains fragmented. The comparative behavior of plant–plant compared with hybrid plant–animal protein systems under frozen conditions is poorly characterized, particularly with respect to air incorporation, melting resistance, and structural integrity over extended storage. Moreover, interactions between plant proteins and bioactive components, such as probiotics, prebiotic fibers, or polyphenols, are still underexplored, despite their potential to substantially influence both nutritional and sensory outcomes in functional or symbiotic products. Sustainability trade-offs associated with emerging processing technologies, including ultrafiltration and fermentation, have rarely been quantified, and the absence of standardized sensory evaluation or industrial-scale validation limits cross-study comparability. To address these challenges, future research should adopt integrated, multiscale approaches that encompass molecular interactions, formulation strategies, processing optimization, and consumer-level assessment, thereby enabling the rational design of plant-protein-enriched ice cream with both functional efficacy and broad consumer appeal.

Nontraditional Proteins and Emerging Sources for Ice Cream

The search for novel protein sources has accelerated due to sustainability, ethical, and nutritional concerns associated with conventional animal and plant proteins. Alternative proteins—derived from insects, microbes, algae, fungi, and precision fermentation—represent a rapidly expanding research frontier [64]. Their distinct amino acid composition, high productivity per land unit, and unique techno-functional properties make them promising candidates for innovative frozen dessert formulations. However, their practical integration requires careful balancing of sensory, functional, and regulatory considerations.

Insect-derived proteins

Edible insects offer high protein density, favorable amino acid profiles, and minimal environmental footprints. Protein extracts from crickets, grasshoppers, silkworm pupae, and black soldier fly larvae have demonstrated promising emulsifying, foaming, and water-holding properties (Table 6) [16,65–71].

In the context of frozen dessert matrices, insect proteins have been incorporated into ice cream formulations with moderate success, improving protein content and thermal stability without major structural defects [16,69].

However, their integration faces considerable regulatory and perceptual barriers [72]. Consumer aversion, particularly in Western markets, and the need for allergenicity testing (due to chitin or cross-reactivity with crustaceans) remain key limitations. Furthermore, flavor masking and color stabilization remain technological challenges, as some insect proteins contribute bitterness or browning during storage.

Insect proteins are nutritionally rich and functionally versatile, providing promising emulsifying and stabilizing properties. However, sensory limitations, allergenicity concerns, and

TABLE 6

Possible application of insect-derived proteins in ice cream.

Source of protein	Crude protein content, (%)	Possible application in ice cream	Reference
Black soldier fly larvae	40.0–45.0	South African startup Gourmet Grubb has created a line of ice cream based on EntoMilk from these insects	[65,66]
Yellow worm larvae (*Tenebrio molitor*)	47.0–60.2	Fruit-berry diet ice cream with chia and quinoa	[67,68]
Melon bug *Coridius vidiatus* and the sorghum bug *Agonoscelis versicoloratus*	27.0 and 28.2, respectively	Gelatin from these insects is used in ice cream 0.5%, which provides improved sensory indicators and biological value	[16,69]
Crickets Gryllus testaceus walker	63.30	Caramelized ice cream with crickets as a flavoring agent and protein fortifier	[70,71]

regulatory uncertainty currently hinder their wide-scale industrial adoption.

Microbial and algal proteins

Single-cell proteins from microbial biomass like yeasts (*Candida utilis*), bacteria (*Methylophilus methylotrophus*), and microalgae (*Chlorella, Spirulina*) are increasingly recognized for their protein yield efficiency, minimal land use, and functional versatility [73,74]. These proteins often display high water solubility, moderate foaming capacity, and the ability to bind fat, making them attractive for low-fat or vegan frozen desserts [75].

Microalgal proteins, in particular, are rich in essential amino acids and bioactives such as pigments and antioxidants, which may provide both functional and nutritional enhancements to ice cream [74]. Nevertheless, strong marine-like flavors, dark coloration limit their sensory acceptability in ice cream.

Microbial and algal proteins exhibit excellent nutritional value and sustainability potential but face challenges in sensory appeal and flavor standardization. Their high variability in pigment and taste profiles necessitates additional processing or masking strategies for incorporation into consumer-acceptable products.

Fungal and mycoprotein sources

Fungal biomass, notably mycoprotein derived from *Fusarium venenatum*, has been proposed as a complete protein alternative with fiber-like texture and low environmental impact [76]. Although well studied in meat analogs, its application in frozen dairy or plant-based desserts is still nascent [77]. Preliminary findings suggest favorable water-binding capacity and structural reinforcement, yet its fibrous texture and potential for off-notes (earthy or mushroom-like) necessitate sensory reformulation.

In addition, proteins extracted from edible mushrooms (e.g., *Pleurotus ostreatus*) exhibit emulsifying and gel-forming potential, but require enzymatic modification to reach solubility thresholds appropriate for aerated frozen systems [10].

Fungal and mycoprotein ingredients contribute structure, viscosity, and water retention in frozen matrices but may introduce undesirable flavors or textures. Optimizing enzymatic hydrolysis and purification can improve solubility and expand their applicability in aerated frozen products.

Precision-fermented and cultivated proteins

Advances in synthetic biology have enabled the development of precision-fermented proteins, bioidentical to dairy proteins, produced via genetically modified microbes. Companies such as Perfect Day and Formo have introduced recombinant casein and whey proteins with comparable structural and functional properties to traditional dairy [78]. These proteins enable the creation of lactose-free, animal-free ice cream with authentic sensory and rheological profiles.

Despite strong promise, precision-fermented proteins are constrained by high production costs, limited global regulatory approval, and public concern about genetically engineered ingredients. However, as manufacturing processes mature, these proteins may play a transformative role in reshaping the protein landscape of frozen desserts.

Precision-fermented proteins provide excellent functional mimicry of dairy proteins and potential allergen reduction. Yet, their cost, regulatory barriers, and consumer skepticism toward genetic modification restrict rapid market penetration.

Implementation outlook and strategic considerations

Emerging protein sources—including microbial, insect, algal, fungal, and precision-fermented proteins—offer unique opportunities for the development of lactose-free, animal-free, and functional frozen desserts. Their generally high digestibility, nutritional density, and in some cases neutral flavor profiles enable broad formulation potential.

Nevertheless, implementation in ice cream remains constrained by a constellation of regulatory, functional, sensory, and economic factors. Regulatory uncertainty and variable consumer acceptance represent key hurdles, particularly for proteins derived from insects, algae, or fermentation-based systems. Functional inconsistency across protein batches adds complexity to formulation standardization and shelf-life control, whereas sensory issues such as off-flavors, bitterness, or color instability may compromise product appeal.

Furthermore, the cost and scalability of producing nontraditional proteins remain significant concerns, with precision fermentation, for instance, being capital-intensive and currently limited to small-scale, high-value applications.

Despite these challenges, strategic pathways for integration are emerging. Hybrid formulations that blend nontraditional proteins with conventional dairy or plant matrices can enhance both sensory acceptability and functional performance. Technologies such as encapsulation, fermentation, or enzymatic treatment offer further opportunities to mitigate undesirable sensory attributes and improve structural integrity.

Current evidence remains largely confined to laboratory-scale or prototype investigations with limited replication, whereas sensory and consumer acceptance studies are still scarce. Moreover, differing regulatory frameworks across regions complicate industrial scalability.

Future studies should focus on optimizing extraction and modification techniques to improve solubility, mitigate flavor defects, and develop harmonized safety regulations. Collaboration between academia, food technologists, and industry stakeholders will be critical to translating laboratory results into commercially viable, sustainable frozen dessert innovations.

Comparison of Protein Sources

Given the diversity of available protein sources, their comparative evaluation is essential to identify the most promising directions for ice cream innovation. The following Table 7 provides a concise synthesis of advantages, limitations, and practical feasibility across major protein categories.

The comparative overview highlights the distinct maturity levels and application potential of each protein class. Animal-derived proteins remain the technological benchmark, ensuring optimal aeration, emulsification, and sensory appeal. However, environmental and ethical concerns, alongside dietary restrictions, drive interest in plant and alternative sources.

Plant proteins currently represent the most practical nondairy substitutes due to global regulatory acceptance and cost accessibility, though their sensory limitations and incomplete amino acid profiles still require optimization. Microbial, insect, and algal proteins demonstrate strong sustainability credentials but remain at an early development stage, with consumer acceptance and regulatory harmonization acting as critical bottlenecks. Precision-fermented proteins, although offering unmatched functional equivalence to dairy, are constrained by economic and scale-up challenges but may redefine the category once production becomes cost-efficient.

This comparison emphasizes that hybrid approaches combining different protein classes to complement functional and sensory gaps are likely to dominate the next generation of protein-enriched frozen desserts. The integration of sustainability metrics, consumer sensory mapping, and technoeconomic assessment will be essential to guide the rational design of future protein systems suitable for industrial-scale ice cream production.

Functional and Technological Effects of Protein Addition on Ice Cream Quality Parameters

The inclusion of protein ingredients whether dairy, plant-based, or alternative in ice cream formulations profoundly influences the physicochemical properties and sensory quality of the final product. Proteins interact with multiple phases within the ice cream matrix, including fat globules, air cells, and ice crystals, thereby affecting texture, stability, mouthfeel, and shelf life [79]. This section synthesizes current findings on how protein enrichment modulates key technological parameters in frozen dessert systems.

Overrun and air phase stability

Proteins contribute to overrun by stabilizing air bubbles through interfacial adsorption and foam film formation. Whey proteins and caseinates are particularly effective due to their amphiphilic nature and rapid diffusion at air–water interfaces. Studies have shown that moderate concentrations ($\leq\sim$4%) of whey protein isolate enhance overrun and foam stability; however, higher concentrations may increase mix viscosity to the point at which air incorporation is impeded [37].

Plant proteins, in contrast, tend to have weaker foam-forming abilities due to limited solubility and flexibility [80]. Although functionalization techniques such as enzymatic hydrolysis or blending with hydrocolloids can improve their performance, variability remains high across sources. Insect and microbial proteins, though underexplored, have demonstrated moderate foaming capacity but require further optimization to support consistent aeration performance.

Ice crystallization and melting behavior

Proteins play a crucial role in modulating ice crystal formation and melt resistance [81]. Through water-binding and viscosity-enhancing effects, proteins limit the mobility of free water and reduce the rate of ice recrystallization during storage. Microparticulated whey proteins and caseinates have been particularly effective in producing smooth, slow-melting textures [82]. In addition, enzymatic hydrolysates have shown potential to suppress ice recrystallization by reducing ice nucleation sites [21].

Proteins with poor water-binding or solubility (some plant or marine proteins) may have the opposite effect, leading to syneresis or brittle textures if not properly balanced. The impact of nontraditional proteins on ice structuring remains poorly understood and requires further mechanistic studies using advanced imaging techniques (cryo-SEM or confocal microscopy).

TABLE 7

Comparative evaluation of protein sources used in ice cream formulations.

Protein source	Technological feasibility	Sensory impact	Regulatory status	Cost implications	Key limitations
Animal-based	Well-established technologies; excellent foaming and emulsifying properties	Familiar texture and flavor; high consumer acceptance	Fully approved and widely used	Moderate; stable supply chains	Ethical and environmental concerns
Plant-based	Requires formulation optimization and flavor masking; variable solubility	May produce beany or earthy notes; lower creaminess	Approved globally	Low-to-moderate cost	Incomplete amino acid profile; lower digestibility
Microbial/insect-based	Promising but underdeveloped; scalable for powders	Neutral to earthy flavor; low familiarity	Partially approved (region-dependent)	Moderate to high initial investment	Consumer perception; limited industrial data
Precision-fermented	High functional control; replicates dairy protein behavior	Neutral flavor; high structural precision	Regulatory approval emerging (GRAS, EFSA pending)	High production and R&D costs	Scale-up and economic feasibility

Abbreviations: EFSA, European Food Safety Authority; GRAS, generally recognized as safe; R&D, research and development.

Texture, viscosity, and mouthfeel

The impact of proteins on ice cream texture is closely tied to their influence on mix viscosity, fat droplet stabilization, and the formation of protein–polysaccharide networks. Whey protein concentrates and isolates contribute to creamy mouthfeel and fine microstructures, often serving as fat mimetics in reduced-fat or high-protein formulations. However, excessive protein concentration (>4%) may result in gelation or increased hardness, necessitating precise formulation control [8,37].

Plant proteins, such as soy and pea, tend to increase mix viscosity but may also contribute to sandy or grainy textures due to incomplete hydration or interactions with other solids. Techniques such as high-pressure homogenization or particle size optimization have been used to mitigate these effects [83]. The impact of emerging proteins (e.g., mycoprotein or microalgae) on rheology and perceived creaminess remains a promising but underexplored area.

Color, flavor, and sensory attributes

Protein enrichment can significantly alter the sensory profile of ice cream. Dairy proteins generally improve flavor perception by enhancing creaminess and reducing off-notes. In contrast, plant proteins, particularly those derived from legumes, can impart bitterness. The degree of purification, protein denaturation, and the presence of antinutritional compounds influence flavor outcomes.

Novel proteins from insects, algae, or microbes often introduce stronger color hues (green or brown) and nondairy flavor notes. Encapsulation, natural flavor-masking agents, and controlled Maillard reactions have been used to mitigate these effects with varying success.

Sensory panel studies suggest that consumer acceptance of protein-enriched ice cream is strongly influenced by flavor balance, mouthfeel, and perceived health benefits [84]. In particular, blends of proteins with prebiotics or fruit-derived ingredients may enhance hedonic perception while delivering functional value.

Legislation, labeling, and consumer perception

The successful incorporation of protein ingredients into ice cream formulations, particularly those derived from novel or nontraditional sources, requires careful consideration of regulatory frameworks, labeling standards, and consumer expectations. These factors not only determine market accessibility but also influence product positioning and acceptance.

Regulatory frameworks for protein-enriched ice cream

In most jurisdictions, ice cream is defined and regulated as a composite dairy or nondairy frozen dessert with specific compositional standards. For example, EU regulation number 1308/2013 and Codex Alimentarius define "ice cream" with reference to minimum milk fat and milk protein content, complicating the inclusion of nondairy proteins under traditional labeling categories.

The addition of novel proteins such as insect-based, algal, or precision-fermented proteins is subject to additional scrutiny. In the EU, Regulation (EU) 2015/2283 governs the authorization of “novel foods,” requiring safety assessment, toxicological data, and nutritional evaluation prior to market approval. The United States Food and Drug Administration, by contrast, employs the GRAS mechanism, although the threshold for inclusion of bioengineered proteins remains stringent.

Labeling requirements vary significantly across regions. In some countries, fortification thresholds must be met for the claim “high in protein” (e.g., ≥12% of energy from protein in EU); whereas allergen declaration rules apply to all known allergens including soy, milk, eggs, and increasingly, insects or their derivatives.

Labeling challenges and strategic communication

Protein-enriched frozen desserts occupy a complex space between indulgence and health-oriented product categories. Labeling thus serves as a critical interface for both regulatory compliance and consumer engagement. Challenges arise in conveying protein quality (e.g., biological value or digestibility), distinguishing between animal and plant-based sources, and navigating the emerging terminology around “alternative,” “functional,” or “hybrid” proteins.

Studies have shown that consumers often misinterpret protein-related claims, especially when paired with terms such as “natural,” “clean-label,” or “sustainable,” leading to either exaggerated health perceptions or confusion about product composition [85]. Strategic labeling should therefore balance legal obligations with transparent and science-based messaging to foster trust and differentiation in a competitive market.

Front-of-pack labels, nutrient profiling systems, and ecolabels (carbon footprint, protein source sustainability) are increasingly adopted, though their effectiveness depends on regional literacy, dietary norms, and the credibility of certifying authorities.

Consumer attitudes and behavioral drivers

Consumer perception of protein-enriched ice cream is shaped by a complex interplay of nutritional awareness, ethical concerns, sensory expectations, and price sensitivity. Although interest in high-protein foods has risen, particularly among health-conscious, athletic, and aging populations, this does not always translate to purchase intent, especially when taste or texture is compromised [86].

Acceptance of nontraditional proteins remains highly variable. Although plant-based proteins have become mainstream in many markets, proteins from insects, fungi, or microbial fermentation are still subject to significant neophobia and “disgust” barriers. Cultural familiarity, previous exposure, and framing all influence acceptance trajectories.

Importantly, trust in the brand and perceived transparency of information emerge as key enablers of adoption. Products that communicate their nutritional, environmental, and technological attributes clearly are more likely to succeed in bridging the innovation–acceptance gap.

Challenges, limitations, and future research priorities

Despite notable advances in protein-enriched ice cream formulations, significant scientific and practical challenges remain.

Balancing functional performance with sensory quality is particularly critical: high protein concentrations can enhance nutritional value but often compromise texture, overrun, and flavor, especially for isolates or hydrolysates [24,58]. Variability in solubility, flavor, and functional performance—common in plant-based and emerging proteins—further complicates formulation, whereas limited understanding of protein interactions with stabilizers, fats, and air restricts predictability during scale-up and frozen storage.

Technological innovations, including enzymatic, physical, or precision-fermented protein modifications, offer opportunities to enhance solubility, digestibility, and texture. However, industrial scalability is constrained by production costs, regulatory approval, and public perception [61]. Laboratory-scale studies dominate the literature, and evidence under real-world industrial conditions remains scarce.

Figure 1 summarizes the main challenges and potential development directions for major protein groups, visually capturing technological, sensory, regulatory, and economic considerations.

Further research should integrate molecular- and systems-level approaches to elucidate protein–fat–air–ice interactions, optimize sensory attributes, and assess sustainability. Comprehensive life cycle analyses and technoeconomic evaluations will be essential to align protein innovation with environmental and nutritional goals. Interdisciplinary efforts combining formulation science, sensory evaluation, and regulatory insight will ultimately enable the design of consumer-accepted, functional, and sustainable protein-enriched frozen desserts.

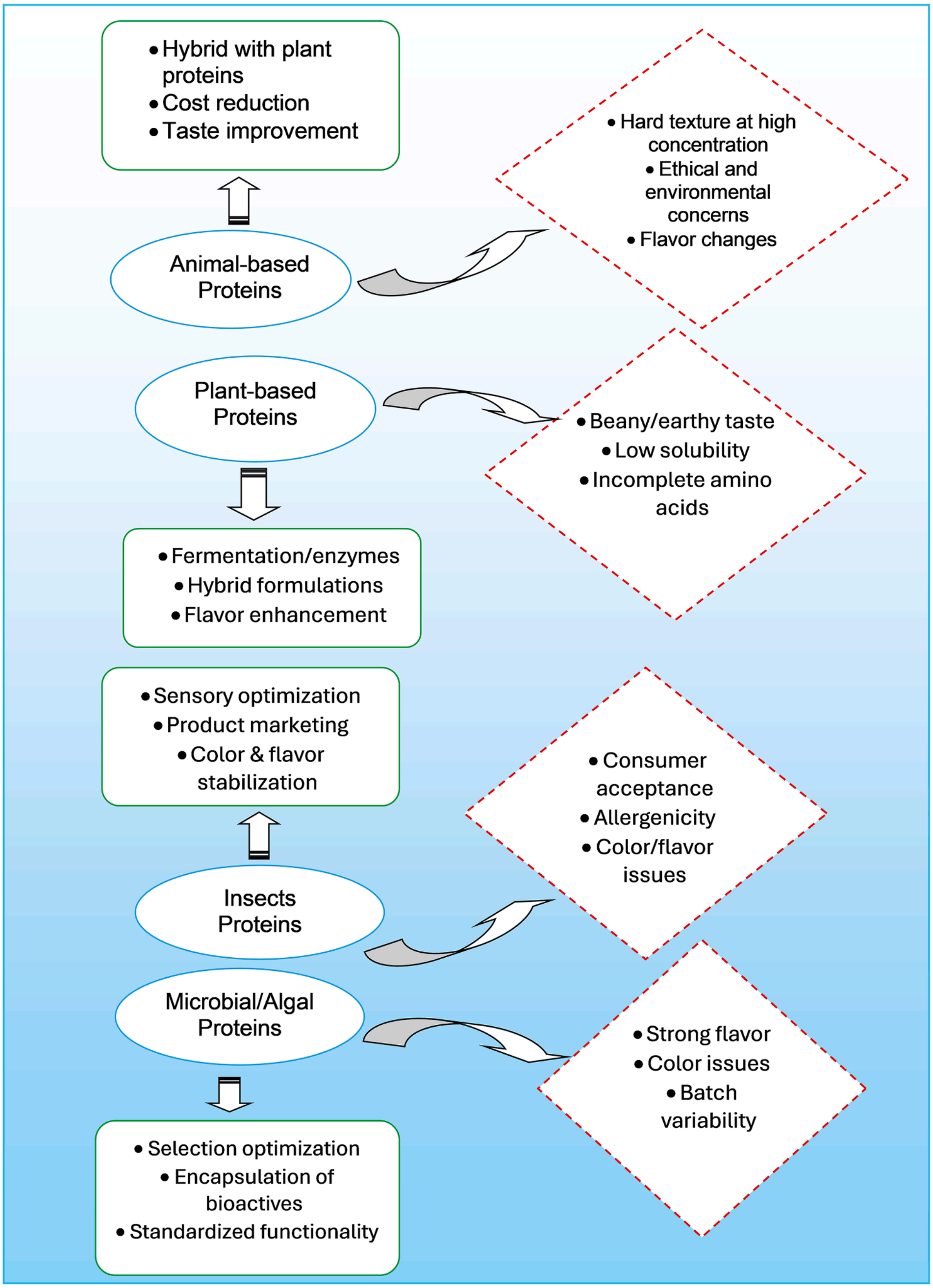

FIGURE 1. The main challenges and potential development directions for major protein groups.

In conclusion, protein fortification of ice cream represents a promising convergence of nutritional enhancement, technological innovation, and sustainability goals. Although dairy-derived proteins continue to serve as the functional benchmark, alternative sources such as plant, microbial, insect, and precision-fermented proteins are expanding formulation opportunities and contributing to the diversification of high-protein frozen desserts. However, the successful integration of these ingredients requires addressing challenges related to formulation stability, sensory optimization, regulatory adaptation, and consumer acceptance.

Future research should focus on elucidating the molecular mechanisms governing protein behavior in multiphase frozen matrices and validating these findings through large-scale industrial and sensory trials. Comparative studies assessing digestibility, bioavailability, and long-term storage stability of alternative proteins would strengthen their scientific credibility. From an industrial perspective, the development of cost-efficient hybrid formulations that combine conventional and novel proteins may provide a practical route toward achieving both nutritional and sensory balance. In parallel, advances in enzymatic modification, encapsulation, and fermentation can further enhance solubility and flavor performance.

At the policy level, harmonized international regulations and transparent labeling standards are needed to accelerate market entry of novel protein ingredients while maintaining consumer trust. Overall, continued interdisciplinary collaboration among food technologists, nutrition scientists, and regulatory bodies will be essential to translate current research into commercially viable, nutritionally optimized, and sustainable protein-fortified ice creams capable of meeting evolving dietary and environmental demands.

Author contributions

The authors' responsibilities were as follows – AM, MB-O: designed research; MB-O, AM: conducted research; MK: analyzed data; AM: wrote the article; GP: had primary responsibility for final content; and all authors: read and approved the final manuscript.

Conflicts of interest

The authors report no conflicts of interest.

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Data availability

Data described in the manuscript, codebook, and analytic code will be made available upon request pending application and approval.

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