International Journal of Food Science and Nutrition
www.foodsciencejournal.com
E-ISSN: 2455-4898
Received: 09-10-2026, Accepted: 08-11-2026, Published: 23-11-2026
Volume 11, Issue 4, 2026, Page No. 182-190

Next-generation proteins for sustainable nutrition: Plant, Algal, Fungal and Fermentation-derived proteins

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DOI: https://doi.org/10.66856/ijfsn.2026.11.4.11208

Abstract
Growing demand for dietary protein, pressure on natural resources, and the need for resilient food systems have accelerated interest in next-generation protein sources. Plant, algal, fungal and fermentation-derived proteins offer diverse nutritional and technological opportunities and potential routes to more resource-efficient protein production. This review highlights these emerging protein platforms from nutritional, technological, environmental and translational perspectives. Quality of amino-acids, digestibility, antinutritional factors and techno-functional properties of plant proteins from legumes, cereals, oilseeds and underutilized crops. Algal proteins are evaluated as nutrient-dense resources with added pigments, minerals and bioactive compounds, while fungal proteins and mycoprotein are evaluated for their protein quality, dietary fiber content and unique textural properties. Platforms for production of tailored nutritional and functional ingredients are reviewed, namely microbial biomass proteins and precision-fermented recombinant proteins from fermentation, which are rapidly developing. Emphasis is placed on protein extraction, fractionation, emerging processing technologies, digestibility, amino-acid availability, protein–matrix interactions and the generation of bioactive peptides. The review covers sustainability indicators such as land and water demands, greenhouse gas emissions, energy demand, resource use efficiency and circular use of agricultural and food processing residues. Key barriers to commercial translation are discussed, including safety, allergenicity, regulatory considerations, consumer acceptance and economic feasibility. We also discuss emerging opportunities involving hybrid protein systems, precision fermentation, biorefinery approaches, artificial intelligence and food-matrix engineering. An integrated assessment of nutritional quality, technological functionality, environmental performance and consumer acceptability could facilitate the creation of affordable and scalable protein foods that could contribute to sustainable nutrition and future food security.

Keywords: Alternative proteins, plant proteins, algal proteins, mycoprotein, precision fermentation, sustainable nutrition

Introduction

The world's protein supply is undergoing a period of significant change, driven by population growth, increased demand for protein-rich foods, environmental pressures and the need for more resilient food systems. Animal-derived proteins are generally of high quality in terms of amino acids and have a favorable digestibility but their production can require substantial inputs of land, water, feed and energy. These forces have led to a diversification of the protein pipeline by plant, algal, fungal and fermentation based platforms [1, 2].

Legumes, cereals, oilseeds, pseudocereals and underutilized crops are still providing ever more diverse protein resources, making plant proteins the most established alternative. However, amino acid limitations, antinutritional factors, reduced digestibility and variable techno-functional properties can limit their direct substitution for animal proteins [3, 4]. Algal proteins have received much attention since microalgae can produce large amounts of protein biomass while producing other valuable compounds and possibly using non-arable resources [5]. Another biological platform is provided by fungal proteins and mycoprotein, combining protein with dietary fiber and unique structural properties [6]. More recently, fermentation technologies have expanded the protein landscape by microbial biomass production and precision fermentation, where microorganisms are engineered to produce specific proteins under controlled conditions [7].

Next-gen proteins are therefore not just about the meat or dairy replacement. At the same time, nutritional adequacy, digestibility, bioavailability, food functionality, sensory quality, safety, affordability and environmental performance must be taken into account. Hybrid protein systems and integrated biorefinery approaches can further enhance nutritional and technological performance. Hence, this review covers plant, algal, fungal and fermentation derived proteins as interconnected platforms for sustainable nutrition including nutritional quality, production and processing, functional properties, food applications, sustainability, safety, consumer acceptance and future technological opportunities.

Methodology

1. Review design

We adopted a structured narrative review methodology to critically synthesize recent evidence on next-generation proteins for sustainable human nutrition. The review focused on four major protein platforms, namely plant-based proteins, algal proteins, fungal/mycoprotein systems and fermentation-derived proteins. This methodology was developed to incorporate nutritional, technological, environmental and translational evidence rather than

considering protein replacement as a sustainability issue alone.

The review was conducted through a staged process of evidence identification and synthesis based on principles of systematic review; it was not considered a formal systematic review or meta-analysis.

2. Literature-search strategy

The review included literature from January 2021 to September 2026. Searches were conducted in PubMed/MEDLINE, Scopus, Web of Science, ScienceDirect and Google Scholar.

Search terms were combined using Boolean operators and included:

"alternative proteins" AND sustainable nutrition "plant proteins" AND nutritional quality "plant protein" AND digestibility "plant protein" AND antinutritional factors "plant protein extraction" AND food "algal protein" AND sustainable food "microalgae protein" AND food application "fungal protein" AND mycoprotein "mycoprotein" AND nutrition "microbial protein" AND food "precision fermentation" AND protein "precision fermentation" AND sustainable food "fermentation-derived protein" AND food "alternative protein" AND food processing "alternative protein" AND consumer acceptance "alternative protein" AND life cycle assessment "alternative protein" AND food safety "novel protein" AND allergenicity

Relevant recent review articles, systematic reviews and high impact primary studies were then searched for additional studies published during the selected period.

3. Inclusion criteria

Eligible studies were those that addressed one or more of the following:

nutritional composition and protein quality; amino-acid composition and digestibility; protein extraction, isolation or fractionation; modification and emerging processing technologies; techno-functional properties; bioactive peptides or health related functionality; food formulation and product applications; environmental sustainability and resource use; safety, allergenicity or regulatory considerations; consumer acceptance and sensory characteristics; or scale-up, economics and commercialization.

Human studies, systematic reviews, meta-analyses and peer reviewed reviews were given priority for translational conclusions. Mechanistic studies, laboratory and animal studies, were included mainly to elucidate nutritional or technological mechanisms.

4. Exclusion criteria

Studies were excluded if they reported only non-food applications, if the protein source was not adequately characterized, if the work was not related to sustainable nutrition, if only conference abstracts were available or if there was insufficient methodological information. Duplicate publications were excluded.

5. Evidence classification

The collected evidence was divided into four general groups: nutritional evidence, technological evidence, sustainability evidence and translational evidence. Human evidence was separated from mechanistic and animal evidence wherever possible. Special attention was given to differences between protein ingredients and finished foods, as the quality of protein, its digestibility and environmental performance can change substantially after processing.

6. Synthesis approach

The review was built stepwise, covering (i) the alternative-protein landscape, (ii) source-specific nutritional characteristics, (iii) production and extraction technologies, (iv) digestibility and bioavailability, (v) food functionality and applications, (vi) environmental sustainability, (vii) safety and consumer acceptance, and (viii) future technological and commercial opportunities.

The reason for this approach was to provide an integrated assessment of the ability of the emerging protein platforms to meet nutritional, technological, environmental and consumer requirements simultaneously.

Next-Generation Proteins: The Emerging Sustainable Protein Landscape

The move to next generation proteins is being driven by the need for diversification of supply of proteins while reducing pressure on land, water and other resources. Alternative proteins are present in a wide variety of resources from the plant, algal, fungal and microbial domains, each with specific nutritional and technological properties [1,2]. The most established platforms today are plant proteins from soybean, pea, chickpea, lentil, faba bean, cereals, pseudocereals, oilseeds and non-conventional plants. The key advantages include the wide availability in agriculture, the relatively mature processing infrastructure and the opportunities to combine complementary amino-acid profiles [3]. However, their nutritional and functional performance depends on species, cultivar, extraction method and processing history. Algal proteins are another avenue, as microalgae can accumulate significant biomass of protein as well as other micronutrients and bioactive compounds, although cell-wall disruption, sensory characteristics and processing costs remain important challenges [4,5]. Biological growth and fermentation produce fungal proteins like mycoprotein, which can contribute protein, fiber, and meat-like structural attributes [6]. Proteins from fermentation take it a step further, using microorganisms as the protein biomass or as production platforms for particular recombinant proteins. Precision fermentation allows for the production of specific proteins such as dairy or egg proteins without the use of the conventional animal source [7]. Therefore, the sustainability of next-generation proteins cannot be assessed solely on the basis of their biological origin. Cultivation conditions, substrate requirements, energy demand, downstream processing, formulation and transport can have a significant impact on the environmental performance. Current evidence is increasingly in favor of a multidimensional assessment including protein quality, digestibility, resource efficiency, technological functionality, consumer acceptance and safety. Thus, the most promising future systems may involve complementary protein sources, circular feedstocks and integrated processing, rather than dependence on a single alternative protein category.

Major Next-Generation Protein Platforms and Their Functional Characteristics

1. Plant-derived proteins

Proteins from plants are the most advanced class of next generation proteins. Legumes such as soybean, pea, chickpea, lentil and faba bean are particularly important because they contain relatively high concentrations of protein and can be processed into concentrates, isolates, flours and texturized ingredients [3, 8].

Plant proteins are nutritionally valuable, but differ from animal proteins in amino-acid composition and digestibility. Cereal proteins may be relatively low in lysine, while many legume proteins are lower in the proportion of sulphur-containing amino acids. Complementary combinations of cereals and legumes can thus improve the amino-acid balance [9].

Plant proteins also contain compounds such as phytate, tannins, protease inhibitors and other antinutritional factors that may interfere with protein digestion or mineral bioavailability. Some of these constraints can be mitigated by processing methods such as soaking, germination, fermentation, enzymatic treatment, extrusion and thermal processing.

2. Pea, legume and underutilised plant proteins

Pea protein has become an important food ingredient due to its relatively high protein content and useful emulsifying, water-binding and gel-forming properties [8]. Dry fractionation may offer a relatively resource-efficient route to protein-rich ingredients, while wet extraction can provide higher protein purity.

Protein diversification opportunities are not limited to major crops; e.g. unconventional food plants and agricultural residues. Green leaves with Rubisco, fruit-processing residues, oilseed meals and other underutilized plant materials could contribute to circular protein production [10].

However, the sustainability advantage of unconventional plant proteins depends on whether disproportionate water, energy or chemical inputs are required for extraction and purification. Thus, full exploitation of the biomass and integration with other coproduct streams are important considerations.

3. Plant protein extraction and fractionation

Typically, the conventional extraction of plant proteins involves milling, aqueous extraction, pH adjustment, centrifugation and precipitation. But these processes can alter the structure of proteins and require large amounts of water or chemical reagents.

Emerging methods are ultrasound assisted extraction, microwave assisted processing, pulsed electric fields, high pressure processing and enzyme assisted extraction. These technologies could enable cell disruption and protein recovery, and possibly reduce the severity of the processing [11].

Dry fractionation, which involves milling and subsequent air classification to produce protein-rich fractions with low water use, is another option. Such approaches may allow retention of native protein functionality but may result in lower purity than with wet extraction.

The optimal extraction method thus depends on the intended application. A highly purified isolate may be desirable for beverages or emulsions, whereas a protein-rich flour or concentrate may be more suitable for bakery products, snacks or high-fibre foods.

4. Algal proteins

Microalgae and other edible algae have received attention due to their ability to produce protein-rich biomass under conditions that are very different from conventional agriculture. The most studied food-grade microalgae are species such as Arthrospira and Chlorella [5, 12].

Algal biomass may also contain pigments, lipids, vitamins, minerals and other bioactive compounds, offering the possibility of multifunctional ingredients. Protein extraction can give you concentrates or isolates that have emulsifying, foaming and water-binding properties.

But the nutritional promise of algal proteins comes with technological limitations. Cell walls can make proteins less accessible and harder to digest, and pigments and other compounds can contribute to strong colors, aromas or flavors. Therefore, cell disruption and subsequent purification are essential steps in the manufacture of consumer-acceptable ingredients [12].

5. Algal protein production and sustainability

The environmental performance of algal protein is highly dependent on the species and the cultivation strategy. Though microalgae can be grown on non-arable land and might need less freshwater than some terrestrial protein systems, the harvesting, dewatering, drying and extraction are energy intensive and can significantly add to the environmental footprint [13].

Life-cycle assessments therefore have to consider the whole production chain and not just the cultivation. Resource efficiency may be improved by heterotrophic cultivation, renewable energy integration, nutrient recycling and biorefinery models.

Recent studies suggest considering algal protein as a complementary platform for protein rather than as a universal replacement for conventional proteins. Its highest sustainability potential may be achieved when protein recovery is combined with the production of pigments, lipids and other high-value compounds [13, 14].

6. Fungal proteins and mycoprotein

Fungal proteins are proteins from edible mushrooms, filamentous fungi, yeasts and mycelial biomass. Mycoprotein is especially interesting because it is produced by fermentation and creates a fibrous biomass that can provide a meat-like structure [6].

Mycoprotein can also preserve a more complex food structure containing protein, fiber and other cellular components, compared to isolated plant-protein ingredients. Human studies have examined possible effects on appetite, energy intake, glycemic responses, cholesterol and muscle protein synthesis [15].

Agricultural or food-processing residues can be used as substrates in fungal fermentation, creating opportunities for circular bioeconomy systems. However, strain selection, contamination control, downstream processing and validation of safety are essential.

7. Fungal protein preparation and functionality

Fungal protein can be produced by submerged or solid-state fermentation or related cultivation systems. The growth rate, protein yield, amino acid composition and the formation of

desirable or undesirable metabolites are influenced by the strain characteristics [16].

Processing may alter the structure and function of fungal proteins. Mechanical disruption, enzymatic hydrolysis and fractionation can yield protein rich ingredients or bioactive peptides. Fungal proteins may also have emulsifying, gelling and water-binding properties of relevance for meat analogs, bakery foods and protein-enriched formulations.

It is therefore necessary to consider nutritional quality, biomass production, food functionality and safety at the same time in the development of fungal proteins.

8. Fermentation-derived and microbial proteins

Fermentation proteins can be classified generally as biomass proteins and precision fermented recombinant proteins. In biomass fermentation, the microorganism is the food ingredient. Engineered microorganisms produce the specific target protein in precision fermentation, and it is subsequently recovered and purified [7, 17].

Microbial biomass can be a source of high protein productivity and can utilize substrates that do not directly compete with conventional food crops. Food uses of filamentous fungi, yeasts and selected bacteria are under investigation.

Precision fermentation is a different technology paradigm. Instead of replicating the entire animal, microorganisms can be used to produce selected proteins like β-lactoglobulin, casein, ovalbumin, and other functional proteins. In this way, some specific functional properties that are difficult to obtain from plant proteins alone can be reproduced [17].

Table 1: Nutritional and functional characteristics of major next-generation protein platforms

Protein platform	Representative sources	Key nutritional/functional characteristics
Plant proteins	Soy, pea, chickpea, lentil, faba bean, cereals, oilseeds	High availability; variable amino acid balance; good emulsification, gelation and water binding properties
Algal proteins	*Arthrospira*, *Chlorella*, other edible microalgae	High protein potential Additional pigments, minerals and bioactives Cell-wall and sensory challenges
Fungal proteins	Mycoprotein, edible fungi, yeast and filamentous fungi	Protein + fiber Good amino acid profile in selected systems Fibrous texture Production by fermentation
Microbial biomass proteins	Yeasts, bacteria, fungi	Rapid biomass production Potential use of alternative substrates Scalable fermentation
Precision-fermented proteins	Recombinant dairy and egg proteins	Directed protein synthesis Precise control over composition Ability to reproduce specific functional properties
Hybrid protein systems	Plant + algal, plant + fungal, plant + fermented proteins	Complementary amino acids and functionality Potential for enhanced nutritional and sensory performance

Footnote: Nutritional quality and functionality vary substantially with species, cultivar, strain, cultivation conditions, extraction method, processing severity and final food matrix. Protein content alone should not be interpreted as equivalent to protein quality or bioavailability.

Source: Adapted and synthesised from recent literature on alternative proteins, plant proteins, algal proteins and fungal proteins [1–6, 8, 12, 13, 16].

Processing, Digestibility, Bioavailability and Food Applications

1. Protein quality and amino-acid availability

Protein quality is determined by amino-acid composition, digestibility and the availability of absorbed amino acids for physiological functions. The nutritional value of some alternative proteins cannot be determined from crude protein concentration alone, although they may provide substantial quantities of protein [18].

Individual sources of plant proteins often lack limiting essential amino acids and are therefore prone to complementary formulation. An improvement in the balance of amino-acids can be achieved by combining legumes and cereals. They can also be combined to create more nutritionally balanced formulations as well.

Algal and fungal proteins can have fairly favorable amino-acid profiles but there are still substantial species-specific differences. Processing can also influence protein digestibility by breaking down cellular frameworks, denaturing proteins and reducing antinutritional factors.

2. Antinutritional factors and digestibility

Plant proteins can be affected by phytate, tannins, protease inhibitors and lectins in digestibility and nutritional availability. The magnitude of these effects depends on the source, concentration and processing.

Fermentation can reduce some antinutritional factors, releasing peptides and changing protein structure simultaneously. Other methods to enhance digestibility include soaking, germination, thermal processing and enzymatic hydrolysis.

But aggressive processing is not always what you want. Excessive heating can cause protein aggregation or Maillard reactions, which reduce the availability of certain amino acids. Protein processing should therefore be optimized, not maximized.

3. Protein extraction and structural modification

The extraction process determines the purity, the molecular framework, and the functional behavior of the protein. Alkaline extraction and isoelectric precipitation are still common for plant proteins, but alternative methods can reduce chemical and water use [11].

Ultrasound can improve mass transfer and cell disruption, high pressure processing can change protein conformation, pulsed electric fields can increase cell permeability and enzymatic hydrolysis can change molecular size and functional properties.

Processing and functionality have a very context dependent relationship. Structural unfolding can expose hydrophobic groups and increase interfacial activity but excessive aggregation can decrease solubility. The processing should thus be geared to the intended food application.

4. Emerging technologies for protein functionality

Next generation protein ingredients tend to need some kind of structural modification to achieve the functionality expected from traditional animal proteins. The process of

high-moisture extrusion is especially relevant in the production of fibrous structures of plant-based meat alternatives.

Emerging non-thermal technologies such as high-pressure processing, pulsed electric fields, ultrasound and cold plasma can modify protein structure while potentially reducing thermal damage [19]. The technologies can improve solubility, emulsification, gelation and textural properties.

The functionality of proteins can be further modified by enzymatic cross-linking, controlled hydrolysis and protein-polysaccharide interactions. In the future, processing alternative proteins will probably involve combinations of physical, enzymatic and fermentation-based approaches.

5. Digestibility and gastrointestinal fate

Ultimately, the nutritional value of an alternative protein depends on what happens after it's consumed. Proteins are digested by stepwise hydrolysis in the stomach and small intestine; amino acids and peptides are then absorbed.

Digestive behavior can be influenced by protein structure, food matrix, processing and interactions with fiber and other components. Recent comparisons of plant-based meat analogs suggest that some products may have lower bioavailability of protein or micronutrients compared to conventional meat depending on formulation and degree of processing [20].

Thus, protein evaluation should feature more and more simulated gastrointestinal digestion, amino-acid release, peptide profiling and, where possible, human absorption studies.

6. Bioactive peptides from next-generation proteins

Alternative proteins can not only be used as nutritional protein sources but also as precursors of bioactive peptides. The enzymatic hydrolysis and the gastrointestinal digestion can release peptide sequences with antioxidant, antihypertensive, antimicrobial or metabolic activities.

Bioactive peptides are especially studied in plant proteins, but fungal and algal proteins may provide additional peptide diversity [21]. The biological significance of these peptides is dependent on their resistance to digestion, absorption and interaction with physiological targets.

This provides an opportunity to design next generation protein foods with essential amino acids and secondary health-related functionality.

7. Food applications

Plant proteins are already being added to drinks, bakery products, snacks, protein bars, meat alternatives and dairy alternatives. The proteins from pea and soybean are of particular interest owing to their well-established extraction technologies and functional properties [8].

Algal proteins have been studied in bakery products, beverages, yogurt type products, snacks and meat alternatives. Due to limitations in color and flavor their use is often restricted and therefore selective protein recovery and deodorization are important.

The fibrous character of mycoprotein makes it naturally suitable for meat-like applications. Fungal biomass can also be used in patties, nuggets and hybrid products.

Precision fermented proteins may be particularly useful where a specific functional property is needed, such as foaming, emulsification, gelation or dairy-protein functionality [17].

8. Plant-based meat alternatives

One of the most visible applications of next-generation proteins are plant-based meat analogs. Product development often involves extrusion, shear cell processing, protein texturisation and incorporation of fats, binders and flavor systems.

The trick is to reproduce the sensory and structural characteristics of meat, without sacrificing nutritional quality. Recent literature has highlighted differences in quality of protein, bioavailability of micronutrients, sodium content and extent of processing between products [20, 22].

Thus, the nutritional quality of alternative proteins should be assessed at the level of the final product rather than only the protein ingredient used.

9. Hybrid protein formulations

Limitations of individual platforms can be overcome by combining protein sources. Cereal–legume combinations may improve amino-acid complementarity and plant–algal or plant–fungal systems may increase protein density, fiber content or texture.

Hybrid systems also have the potential to decrease the sensory burden of individual components. For example, relatively neutral plant proteins could be blended with smaller amounts of algal proteins to boost nutritional density without excessive color or flavor.

Such formulations should be optimized for amino-acid score, digestibility, texture, sensory acceptance, cost and environmental performance, rather than just protein concentration.

10. Consumer acceptance and sensory performance

Consumer acceptance is a key factor in whether next-generation proteins can achieve meaningful penetration into diets. The acceptance depends on sensory characteristics, familiarity, price, perceived healthiness, cultural appropriateness and food neophobia [23].

The color and marine or grassy flavors can be strong sensory barriers for microalgae. Plant-based meat alternatives are often criticized for high levels of processing, strange textures or ingredient complexity. Meat-like structure may be an advantage for fungal proteins, but unfamiliarity could still be a barrier.

Precision fermentation raises additional questions of genetic engineering, naturalness, food safety and regulatory transparency. Hence, technical performance alone will not ensure market adoption.

11. Nutritional reformulation of alternative protein foods

When formulating alternative protein foods, the amount of protein, in addition to iron, zinc, calcium, vitamin B12, essential fatty acids, sodium, fiber and overall energy density, should be taken into account.

Some plant-based meat products offer beneficial fiber and less saturated fat than traditional meat, but the composition of products can vary greatly. Some highly processed products may contain high amounts of sodium or several functional additives [20, 22].

Nutritional optimization should therefore include fortification where appropriate, protein blending, reduction of sodium, increased micronutrient bioavailability and incorporation of whole-food ingredients.

12. Food-matrix interactions

In foods proteins do not work in isolation. Solubility, aggregation, digestion and sensory properties are influenced by interactions with polysaccharides, lipids, phenolics and minerals.

For example, protein–polysaccharide interactions have been shown to enhance emulsion stability or gel structure. Protein–polyphenol interactions can modify protein functionality and phenolic bioavailability. Fiber may affect gastrointestinal digestion by altering the viscosity and availability of nutrients.

Thus, protein development should consider the final food matrix, not only the isolated protein ingredient as a determinant of nutritional performance.

13. Precision fermentation and targeted protein production

Precision fermentation is a very specific way of producing single proteins. Microbial hosts can be engineered to express specific target proteins, whilst fermentation conditions can be optimized for productivity and downstream recovery [17, 24].

Milk and egg proteins have become prominent targets due to their functional properties that are difficult to be reproduced completely using plant proteins. Recombinant proteins can offer foaming, emulsification, gelation and nutritional properties similar to conventional proteins.

However, scale-up considerations such as production costs, fermentation titers, purification needs, and energy use are still important.

14. Safety and allergenicity

The safety assessment has to consider the source organism, the processing conditions, residual components, contaminants, allergens and novelties. For precision ferments of proteins, the assessment also has to include the production host, residual host-cell proteins, post-translational modifications and allergenicity of the target protein.

Recent work has shown that precision-fermented proteins may differ subtly from their native counterparts due to host-dependent folding, glycosylation and processing characteristics [25]. Therefore, safety assessment should be based on the final food product and not solely on the purified protein.

Table 2: Processing, nutritional challenges and strategies for next-generation proteins

Protein source	Major challenge	Potential processing/solution	Food application
Plant proteins	Limiting amino acids, antinutritional factors, lower digestibility	Germination, fermentation, enzymatic treatment, fractionation, extrusion	Meat alternatives, beverages, bakery, snacks
Algal proteins	Cell-wall resistance, colour, flavour, extraction cost	Cell disruption, enzymatic/physical extraction, fractionation, biorefinery	Beverages, bakery, snacks, functional foods
Fungal/mycoprotein	Strain selection, safety, consumer familiarity	Controlled fermentation, biomass optimisation, texturisation	Meat alternatives, protein-rich foods
Microbial biomass protein	Substrate cost, downstream processing, sensory quality	Fermentation optimisation, biomass recovery, drying	Protein ingredients, foods, supplements
Precision-fermented proteins	Production cost, purification, allergenicity and regulation	Strain engineering, fermentation optimisation, downstream purification	Dairy/egg alternatives, functional ingredients
Hybrid proteins	Compatibility, flavour, processing interactions	Protein blending, extrusion, fermentation, matrix engineering	High-protein foods and next-generation analogues

Footnote: Processing strategies should be selected according to the target nutritional and functional properties of the final food. Improved protein extraction or purity does not necessarily translate into improved digestibility, sensory quality or environmental performance.

Source: Adapted and synthesised from recent literature on protein extraction, food processing, alternative-protein functionality, plant-based foods, fungal proteins and precision fermentation [11, 16, 19–25].

Sustainability, Safety, Translational Challenges and Future Directions

1. Environmental sustainability

The sustainability of next generation proteins can't only depend on the biological origin of the protein, but on the whole production chain. Land use, water consumption, fertilizer requirements, energy demand, cultivation conditions, processing intensity, transportation and waste generation can affect the environmental performance [26].

Plant proteins often benefit from existing agricultural infrastructure, while microbial and algal systems may have high productivity per unit of land. But energy-intensive drying, extraction or purification may offset some environmental benefits.

Therefore, life-cycle assessment should be based on comparable functional units, preferably on the basis of nutritional protein delivered rather than just biomass produced.

2. Circular protein production

Circular-economy approaches offer opportunities to enhance resource efficiency. Sources of protein and fermentation substrates can be obtained from agro-industrial residues, oilseed meals, cereal by-products and food-processing streams.

Fungal and microbial fermentation may be especially appropriate for conversion of low-value substrates to protein-rich biomass. Similarly, algal biorefineries can recover protein together with pigments, lipids and carbohydrates [14, 27].

Thus, integrated systems can generate multiple value added products from a single biomass feedstock to improve economic viability and reduce waste.

3. Economic and scale-up challenges

Success at the laboratory scale does not always translate into commercial viability. Reliable raw materials, scalable extraction, consistent quality, efficient downstream processing and competitive costs are all needed for alternative-protein production.

Harvesting, dewatering and cell disruption can be significant cost and energy burdens for microalgae [28]. The primary cost drivers for precision fermentation production are fermentation productivity and downstream purification.

Thus, future scale-up should integrate techno-economic assessment with life-cycle assessment at the earliest stages of process development.

4. Safety and regulatory landscape

Novel protein ingredients need appropriate assessment of toxicity, allergenicity, microbial contamination, residual processing chemicals and compositional consistency.

Precision fermentation also raises further regulatory issues, as the target protein may be the same or close to a protein already present in food, but produced by a genetically modified microorganism. Recent evidence emphasizes the need to assess the production-related modifications and processing-dependent alterations in allergenic epitopes [29].

Harmonized international frameworks would help to ensure responsible development and appropriate consumer protection.

5. Consumer acceptance and affordability

Without consumer acceptance of the foods resulting from sustainable protein systems, their impact will be limited. Acceptance is driven by sensory properties, familiarity, price, perceived naturalness, cultural context and trust in production technologies [23].

Affordability is also important. Technologies that require highly purified ingredients or energy intensive processing could result in products not accessible to protein insecure populations.

So next generation proteins need to be developed as premium technology products but also affordable components of the mainstream diet.

6. Future directions

Future work should be aimed at integrated protein-system design rather than optimization of individual protein sources. Hybrid formulations of complementary plant proteins with algal, fungal or fermentation-derived ingredients can improve nutritional balance, functionality and sensory performance.

"Machine learning and artificial intelligence can speed up the selection of protein-source, amino-acid optimization, formulation design, sensory prediction and process optimization. Digital modeling can also assist in integrating nutritional and environmental datasets to identify protein systems with good overall performance.

Precision fermentation will likely continue to broaden the array of proteins that can be produced apart from traditional animal agriculture. At the same time, advances in the cultivation of algae, the fermentation of fungi and the fractionation of plant proteins may enable the production of biological biomass to become more resource efficient.

Future research should increasingly integrate proteomics, metabolomics, gastrointestinal digestion models, life-cycle assessment, techno-economic analysis, and consumer science. Multidisciplinary approaches could identify protein systems that perform well in nutritional, technological, environmental and commercial dimensions simultaneously.

Development of culturally appropriate foods will be important as well. Next-generation proteins could be added to traditional porridges, snacks, bakery foods, fermented products and staple foods, not just western-style meat analogs. This could increase familiarity and help accelerate adoption.

Limitations

It is important to consider several limitations when interpreting the evidence synthesized in this review. First, the term “alternative” or “next-generation” protein covers a wide range of materials that vary greatly in composition, production technology and nutritional quality. This makes it hard to compare platforms directly. Second, sustainability estimates vary according to cultivation systems, geographical location, energy sources, processing and system boundaries considered in life-cycle assessments. Third, many studies assess individual protein ingredients rather than finished foods, limiting conclusions regarding actual dietary exposure and consumer relevant functionality. Fourth, evidence for some emerging proteins, especially precision-fermented and novel microbial proteins, is relatively recent compared with the vast literature available for conventional plant proteins. Fifth, laboratory measurements of protein digestibility and functionality do not necessarily predict human nutritional results or market acceptance. Finally, there is a challenge of comparing commercial readiness as regulatory structures differ from jurisdiction to jurisdiction. These limitations highlight the need for standardized nutritional metrics, comparable sustainability assessments, long term human studies and harmonized safety evaluation.

Conclusion

“Next-generation proteins are a growing and increasingly diverse element of future food systems. Proteins from plants, algae, fungi and fermentation processes provide unique methods to increase the variety of proteins available. They also help create food products that use resources more efficiently and have new, interesting nutritional and functional properties.

The future potential of these proteins should not be evaluated only by their concentration. Amino-acid composition, digestibility, bioavailability, processing behavior, sensory properties, food-matrix interactions, safety, affordability and environmental performance are all of equal importance. Each protein platform has its own strengths and weaknesses, suggesting that no single source is likely to offer a universal solution to global protein needs.

Plant proteins are most technologically mature at the moment, but algal and fungal systems offer opportunities for resource-efficient biomass production and additional nutritional functionality. Fermentation proteins add another dimension in that microorganisms can be used either as a protein-rich biomass or as a highly controlled production platform for a given protein.

So the most promising route is proposed to be protein diversification and intelligent combination. Complementary plant proteins, ingredients from algae, fungal biomass and fermentation-derived proteins can be blended to improve nutritional quality, functionality and consumer appeal. Processing, precision fermentation, circular biorefineries and digital formulation will further extend these possibilities.

Finally, the development of sustainable proteins must be based on a total system approach that links nutritional adequacy to environmental responsibility, technological feasibility, safety and consumer needs. Next-generation protein systems could not only replace conventional proteins, but also change the way we produce, process and incorporate proteins into everyday foods. Their successful

contribution to sustainable nutrition will depend on their ability to translate technological innovation into safe, affordable, nutritious and culturally acceptable foods.

Acknowledgements
The authors acknowledge the academic support provided by the Department of Food Processing Technology, Academy of Maritime Education and Training (AMET), Deemed to be University, Chennai, India.

Declarations

Funding
No funding was received for the preparation of this review article.

Conflicts of interest/Competing interests
The authors declare that they have no competing interests.

Consent for publication
Not applicable. The manuscript does not contain identifiable personal data, images or information relating to individual participants.

Availability of data and material
Data sharing is not applicable because no new datasets were generated or analysed during this review. All literature supporting the article is cited in the manuscript.

Code availability
Not applicable. No custom software or computational code was developed or used.

Authors' contributions
NM conceived the review, developed the methodology, conducted the literature search and evidence synthesis, prepared the tables and figures, and wrote the original draft. JW supervised and validated the work and critically reviewed, revised and edited the manuscript. Both authors read and approved the final manuscript and agreed to be accountable for the integrity of the work

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