

The Importance of Next-Generation Protein Sources for Sustainable Food Futures

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DOI:

<https://doi.org/10.57251/jrpfods.2025.4>

Abstract

The transformation of alternative protein raw materials into processed food products represents a critical advancement in addressing global food security, environmental sustainability, and economic efficiency. Compared to traditional livestock systems, alternative proteins—derived from microalgae, insects, microbial biomass, and plant-based sources—offer high yields with minimal resource input and reduced ecological impact. These raw materials can be cultivated under controlled conditions, allowing for consistent, scalable production independent of seasonal or climatic constraints. Modern food processing technologies, including enzymatic hydrolysis, extrusion, fermentation, and spray-drying, enable the effective extraction, enhancement, and stabilization of protein content, improving functionality and shelf life. Economically, the use of agricultural waste streams and low-input biomass sources significantly lowers production costs, promoting resource-efficient circular systems. Furthermore, incorporating these proteins into consumer-ready products such as meat analogs, fortified beverages, and protein-enriched foods improves nutritional accessibility while meeting evolving consumer preferences. Environmentally, this transition supports reductions in greenhouse gas emissions, land degradation, and water usage. Overall, using sustainable ingredients in processed foods helps create a food system that's resilient, nutritious, and economically viable for our growing global population.

Keywords: Sustainable Protein Sources, Cultured Meats, Plant-Derived Proteins, Algae, Insects, Microbial Protein, Yeast Protein

1. INTRODUCTION

The escalating global demand for protein is a multifaceted phenomenon driven by population expansion, evolving dietary patterns, and an increasing awareness of the interconnectedness between human health and ecological sustainability. Traditional animal-based protein production, while historically central to human nutrition, is recognized as a significant contributor to critical environmental perturbations, including substantial greenhouse gas emissions, deforestation, and the unsustainable exploitation of land and water resources (Poore & Nemecek, 2018). Consequently, the imperative to mitigate anthropogenic environmental impact and ensure global food security and nutritional

adequacy has catalyzed the investigation and development of alternative protein sources. Plant-based proteins have emerged as a prominent area of research within this context, representing a potentially sustainable substitute for animal-derived proteins. Plant-derived protein isolates and concentrates, sourced from leguminous crops such as *Glycine max*, *Pisum sativum*, and *Lens culinaris* offer inherent advantages, including a reduced content of saturated fatty acids and the absence of cholesterol, and an antioxidant effect (Han & Baik, 2008; Joehnke et al., 2021).

Recent advancements in protein extraction and processing technologies applied to botanical sources have yielded significant improvements in the functional (e.g., solubility, emulsification)

and sensory (e.g., texture, flavor) attributes of these proteins, thereby enhancing their potential for broader consumer acceptance (Sawant et al., 2025). Furthermore, the application of plant-derived proteins in culinary contexts is expanding, exemplified by the development of novel plant-based structural materials and edible film technologies. Ongoing research is extensively focused on the seamless integration of plant-based protein isolates and concentrates into existing food formulations as direct replacements for animal proteins, with the objective of maintaining or replicating preferred textural and organoleptic characteristics (Onwezen et al., 2021).

Beyond the realm of plant-based proteins, alternative sources such as microbial biomass, algae, and insects represent promising avenues for sustainable protein production. Microbial proteins, derived from organisms including filamentous fungi, yeasts, and bacteria, have demonstrated high protein yields per unit area and a favorable sustainability profile (Sawant et al., 2025). These microorganisms can be cultivated to produce novel protein matrices, exemplified by mycoprotein, often requiring limited land area and capable of utilizing industrial byproducts as growth substrates, thereby contributing to waste valorization. Similarly, algal proteins, derived from species such as *Arthrospira platensis* (spirulina) and *Chlorella vulgaris*, exhibit comparable amino acid profiles to conventional protein sources and demonstrate high digestibility (Smetana et al., 2015a). Algae cultivation necessitates significantly lower resource inputs (e.g., water, land) compared to traditional agricultural practices, positioning it as a vanguard in sustainable protein resource development. Insect-based proteins constitute another noteworthy alternative protein source, characterized by elevated protein content, rapid life cycles, and comparatively low resource requirements. Edible insect species, such as *Tenebrio molitor* (mealworm) and *Acheta domesticus* (cricket), offer a nutritionally dense

biomass that can be incorporated into a diverse array of food products, including snack foods and protein bars (Smetana et al., 2015b). However, the widespread adoption of insect-based proteins faces significant challenges related to limited consumer acceptance and the nascent state of regulatory frameworks governing their production and consumption (Smetana et al., 2015b). Cultured meat, also referred to as cell-based or in vitro meat, represents a potentially transformative sustainable protein substitute. This technology involves the ex vivo cultivation of animal-derived cells within a controlled bioreactor environment, enabling the production of muscle tissue without reliance on traditional animal husbandry. Beyond offering protein with organoleptic properties analogous to conventionally produced meat, this methodology holds the potential to substantially reduce greenhouse gas emissions, land utilization, and water consumption, with reported reductions of up to two orders of magnitude (Hochedlinger & Zepeda, 2023). Nevertheless, challenges related to production costs, scalability to industrial levels, and consumer perception must be effectively addressed prior to the widespread commercialization of this technology.

Consumer perceptions of sustainable protein alternatives represent a critical determinant of their market success. Factors such as sensory attributes (taste, texture), economic considerations (price), and perceived nutritional benefits significantly influence the propensity of consumers to transition towards alternative protein sources (Onwezen et al., 2021). Furthermore, increasing public awareness regarding the ethical and environmental externalities associated with conventional animal agriculture is contributing to the expanding market for plant-based and other alternative protein products (Onwezen et al., 2021). This review addresses global protein demand and the need for sustainable solutions beyond traditional animal farming. Also, this

review examine the potential of alternative proteins—such as plant-based, insect-based, algae-based, microbial (including yeast), and

cultured meats, as shown in the Figure 1 these sustainable protein sources, and their global impacts.

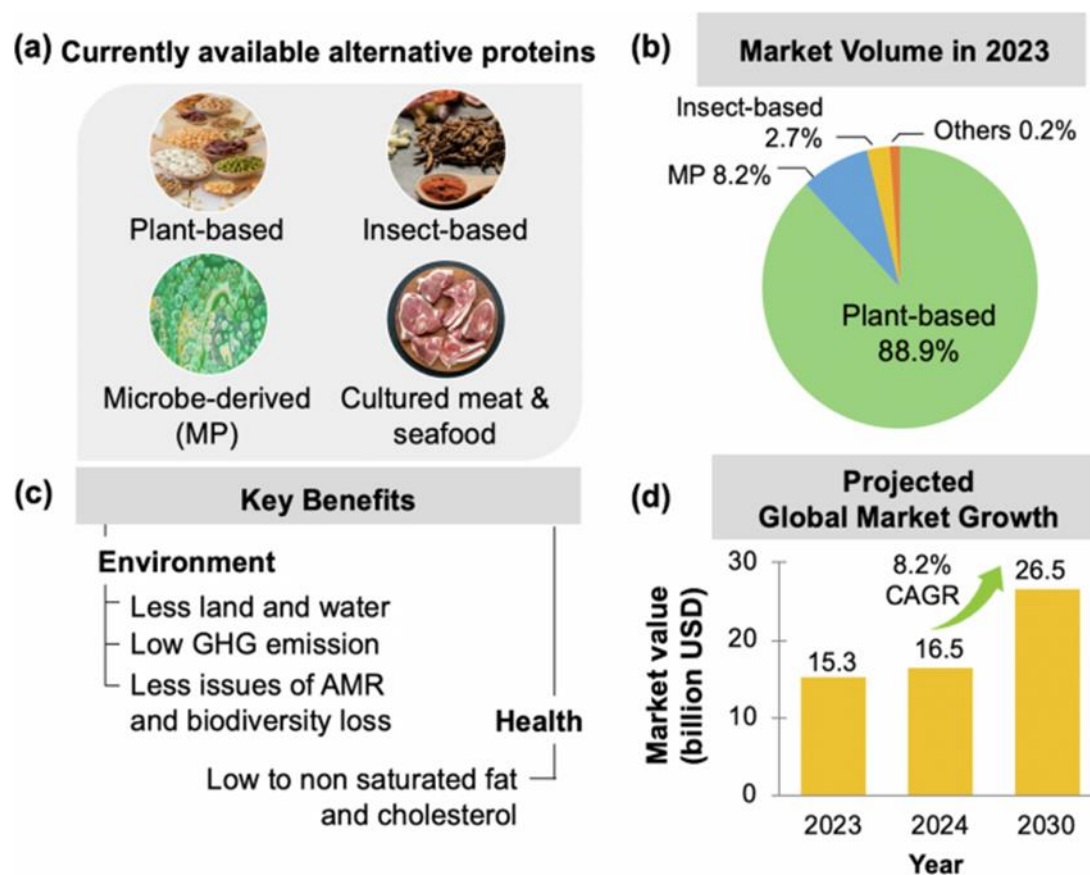


Figure1. Sustainable protein sources, and their global impacts (Malila et al., 2024).

a) The alternative proteins that are presently accessible. b) The total amount of these products sold in the market. c) The main advantages associated with alternative proteins. d) The anticipated expansion of the alternative protein market. (MP stands for protein sourced from microorganisms. GHG (Greenhouse Gas) denotes gases that trap heat in the atmosphere. AMR signifies the ability of microbes to resist drugs designed to kill them. CAGR represents the average annual growth rate of an investment over a specified period, reflecting its compounded returns)

2. ALTERNATIVE PROTEIN SOURCES: ADDRESSING SUSTAINABILITY OPTIONS

Growing global concerns regarding sustainability, food safety, human health, and animal welfare are accelerating the shift toward sustainable protein alternatives (Heppner & Livney, 2025). This burgeoning interest in alternative proteins is evident among both researchers and industry (Motoki & Qin, 2025). Projections indicate that by mid-century, the world will require an additional 265 million tons of protein, a substantial 50% increase from

current levels. Consequently, significant efforts are underway to identify sustainable protein sources to combat food insecurity. Three promising new meat surrogates: microalgae, insects, and cultured meat are exhibit considerable potential as future food sources (Fatima et al., 2023). Insects, algae, and yeasts are gaining prominence as novel protein alternatives due to their sustainable growth practices, efficient biomass recovery, high protein yield, and notable nutrient quality. With innovative, cost-effective, and environmentally friendly production and harvesting methods, these sources are becoming viable alternative

protein options for the future (Barbosa et al., 2024).

2.1 Algae as a Protein Source

Algae represent a promising source of nutritional proteins, including lectins, phycobiliproteins, mycosporine-like amino acids, and their derived hydrolysates and bioactive peptides. These algal proteins and their biomolecules have garnered significant attention for potential applications in nutraceuticals, pharmaceuticals, cosmetics, and functional foods (Leong et al., 2024). As a sustainable and nutrient-rich alternative protein, algae are appealing due to their potential health benefits and reduced environmental footprint (Bahraseman et al., 2025). Developing a sustainable and cost-effective food source rich in essential fatty acids (EFAs) and other bioactive compounds while minimizing environmental impact remains a considerable challenge. In this context, filamentous algae offer easier and more cost-effective harvesting compared to single-celled microalgae, promoting more environmentally friendly large-scale production of biomass and bioactive compounds (Rahaman et al., 2025). Due to their high protein content, microalgae are frequently used as dietary supplements in powders, pills, or tablets. Algal proteins can be efficiently isolated using various extraction methods and serve as excellent food additives. They have also been incorporated into functional foods such as noodles, bread, biscuits, beverages, chocolate, and beer (Ijaola et al., 2024). The current consumer trend indicates a clear intention to diversify protein sources, seeking nutritious, high-quality, and sustainable options to meet dietary needs. Microalgae protein shows significant promise as a vegan protein alternative, with extensive safety evaluations conducted on protein extracted from *Picochlorum maculatum* for human consumption (Group et al., 2024). Furthermore, algae-derived proteins and bioactive peptides exhibit a wide array of

bioactivity and therapeutic properties, offering notable health benefits in mitigating and treating oxidative stress, cardiovascular diseases, cancer, and diabetes (Leong et al., 2024).

2.2 Edible Insects as a Protein Source

The urgent need to identify and implement sustainable protein alternatives is crucial for addressing global food sustainability challenges and mitigating widespread environmental degradation (Onwezen et al., 2021). Edible insects have emerged as a viable solution to enhance food, feed, and nutrient security while contributing to waste management (Abro et al., 2025). Consuming edible insects can provide an advantageous alternative to the traditional food supply chain, which often involves global water waste, land scarcity, malnutrition, and hunger. Beyond their nutritional value, insect proteins demonstrate a broad range of functional properties, including foamability, emulsifying, and gelling abilities. The protein content and amino acid profiles of certain insects reveal good nutritional value and interesting functional characteristics (Queiroz et al., 2023). Promising novel sustainable protein sources include edible insects such as crickets (*Acheta domesticus*) and mealworms (*Tenebrio molitor*), recognized for their high protein content, healthy fats, and various micronutrients (Smetana et al., 2015b).

2.3 Yeast as a Protein Source

With global protein demand steadily increasing over the past two decades, current food research heavily focuses on finding sustainable and healthier alternative proteins. Yeast proteins, being of microbial origin, offer environmentally friendly advantages. They are high-quality proteins with high bioavailability, making them strong candidates for new alternative protein applications in food (Ma et al., 2023). Yeast biomass is an excellent source of protein and other nutrients for developing protein-rich alternatives to animal products (Heppner and Livney, 2025). Achieving this

requires expanding existing production capacity and increasing demand for yeast-based food products. Key research areas include understanding the functional properties of lignocellulosic sugars, lactose, and non-*Saccharomyces* yeast biomass that can be produced from sensitive fermentation (Martin & Chan, 2024). Specific, controlled studies on yeast biomass functionality, correlated with species and growth conditions, are needed to scale up nutritional yeast production and its associated environmental benefits (Martin & Chan, 2024). One study identified 53 yeast strains meeting established criteria, representing 16.6% of the total number, as promising candidates for ingredients in meat products with lower meat content, thereby addressing consumer demand for healthier and more sustainable alternatives (Viveros-Lizondo et al., 2025). Yeast proteins hold significant application potential as alternative proteins with a balanced amino acid composition. They can be hydrolyzed to produce yeast peptides and are used in protein supplements, thinning agents, and meat extenders. Overcoming limitations such as high nucleic acid content and cost, alongside improving functional properties and sensory acceptability, will significantly advance yeast protein applications (Ma et al., 2023).

2.4 Microbial Protein Sources

Microbial protein sources, especially fungi and cyanobacteria, have emerged as potential alternatives to traditional animal and plant-based proteins. Microorganisms have numerous uses in many areas of the food industry, which contributes to the production of various food systems (Dalbanjan et al., 2024). In order to meet the growing demand for protein-based foods globally, microbial protein (MP) has the potential to become an alternative food or feed source (Muys et al., 2023). Microbial bioconversion of valuable materials into nutritious microbial cells also offers a sustainable pathway for the food chain.

Microbial protein, or single-cell protein (SCP), comprises algal biomass, fungi, or bacteria, and is currently utilized as a food source for both humans and animals. Beyond its role in sustainably feeding the global population, SCP production helps mitigate waste disposal issues and reduce production costs, aligning with sustainable development goals. However, for microbial protein to become a significant and sustainable alternative in feed or food, challenges related to raising awareness and achieving broader public and regulatory acceptance must be addressed thoughtfully (Alves et al., 2023).

2.5 Cultured Meat: A Promising Alternative Animal Sources

Traditional meat production and export are fundamental to the economies of agricultural countries. However, the meat industry's negative environmental and social impacts, including deforestation, greenhouse gas emissions, and animal welfare concerns, have escalated with increasing meat demand (Silva & Conte-Junior, 2024). Laboratory-based meat production requires high-efficiency, large-scale technology to develop high-quality meat customized for the livestock agriculture industry, the environment, animal welfare, and human health. However, this field is still nascent, facing significant challenges such as technological limitations and consumer acceptance (Li Ching et al., 2022).

Currently, there is no global legal recognition for laboratory-based meat. Nevertheless, given the high demand for meat analogues, this area of study is expected to contribute to company portfolios, necessitating more funding and research to ensure its safety and meet societal requirements (Ching et al., 2022). Cultured meat is produced by growing animal stem cells, allowing them to undergo growth and division that closely mimics natural cellular development within living organisms. The primary motivations for cultured meat production include minimizing environmental

impact by reducing methane emissions, making meat more economical for consumers, and providing antibiotic-free meat (Samad et al., 2024). Cultured meat offers solutions to increasing protein demands and human health concerns, as well as addressing growing problems related to the environment, animal welfare, and food safety. However, fundamental concerns such as socio-cultural issues, food safety, contamination, synthesis rate, efficiency, and consumer acceptability must be carefully considered when using it for human consumption. As biotechnology advances, many barriers to adopting these alternative proteins are gradually being removed (Fatima et al., 2023).

As the global population expands, the demand for food and animal-derived products significantly increases, posing a considerable challenge to societal progress. Alternative protein production, particularly cell-based meat production, emerges as a promising solution. Addressing complexities such as scalability, genetic modification, and safety concerns will necessitate interdisciplinary approaches to assess cultured meat's potential as a sustainable protein source. The goal is to mimic the sensory and nutritional properties of traditional livestock meat while meeting the demands of a growing global population and reducing environmental impacts (Nunes et al., 2025). Also, Cultured cells require culture media containing various additives. However, these additives raise both environmental and ethical concerns, highlighting the need for alternative solutions to ensure sustainable cell cultivation. Serum and antibiotics, widely used for their vital roles in providing essential nutrients for cell growth and preventing contamination, are difficult to replace, though continuous efforts are underway to develop suitable alternatives. Given that culture media is central to cultured meat production, developing efficient and cost-effective media is essential (Choi et al., 2025).

2.6 Greener Sources: Plant-Based Proteins

Plant-based proteins offer significant environmental advantages compared to traditional animal-derived proteins, playing a crucial role in mitigating climate change, resource depletion, and biodiversity loss. The food industry is a substantial contributor to greenhouse gas (GHG) emissions, with livestock production accounting for approximately 14.5% of the total (Onwezen et al., 2021). Shifting towards plant-based proteins results in considerably smaller carbon footprints because plant agriculture generally requires less land, water, and energy inputs, while also producing lower levels of methane and nitrous oxide (Smetana et al., 2015a). To maintain ecological balance, a transition from animal to plant-based protein consumption may be essential (Langyan et al., 2022).

For instance, the production of soy protein, a prevalent plant-based protein, generates ~0.58 kg of CO₂-equivalent per kg of product. This represents a reduction of over 95% in GHG emissions compared to beef protein production, which generates approximately 27 kg of CO₂-equivalent per kg of product. Plant proteins such as those derived from peas, lentils, chickpeas, and fava beans also contribute to soil fertility, reducing the need for synthetic fertilizers that have high carbon footprints. Furthermore, plant protein production is highly space-efficient; producing one kilogram of plant protein can require up to 18 times less land area than producing one kilogram of its animal-derived counterpart. This substantial saving primarily stems from the reduced land requirements of plant-based diets. Water usage is another critical factor, with lentil production requiring around 1,250 liters of water per kilogram, in stark contrast to the approximately 15,500 liters needed for one kilogram of beef (Poore & Nemecek, 2018). This significant reduction in freshwater consumption can contribute to alleviating water scarcity. The adoption of plant-based diets can directly decrease freshwater usage. Additionally, plant-based protein agriculture necessitates limited

land clearing and habitat conversion, thereby reducing habitat loss and contributing to the preservation of ecosystems (Smetana et al., 2015b).

Plant-based proteins offer distinct advantages over animal-derived proteins by combating biodiversity loss, climate change, and resource depletion (Tso & Forde, 2021). Livestock production contributes to approximately 20% of global GHG emissions (Santo et al., 2020), highlighting the food industry as a major emitter. Given that plants require substantially less land, water, and energy inputs and emit very low levels of methane and nitrous oxide, the consumption of plant-based protein is associated with a smaller environmental footprint (Santo et al., 2020). For example, beef protein production generates around 27 kg of

CO₂ per kilogram, while soy protein production generates approximately 0.58 kg of CO₂ per kilogram, representing a 95% reduction in GHG emissions (Santo et al., 2020). Moreover, plant proteins like those from peas, lentils, chickpeas, and fava beans have low carbon footprints and can improve soil health, reducing the need for synthetic fertilizers with high carbon footprints (Hertzler et al., 2020). Table 1 concisely illustrates that traditional animal farming has a significantly higher environmental footprint (more greenhouse gas emissions, land, and water use) compared to various alternative protein sources. These alternatives, including plant-based, microbial, algal, insect, and cultured meats, offer promising solutions for more sustainable protein production due to their generally much lower environmental impact.

Table 1. Environmental Impact Comparison of Various Protein Sources

Protein Source	Greenhouse Gas (GHG) Emissions (CO ₂ -equivalent per kg of product)	Land Use	Water Use	Other Environmental Benefits/Risks	References
Traditional Animal-Based Proteins	High (e.g., Beef: ~27 kg CO ₂ -eq/kg, up to 60 kg CO ₂ -eq/kg from search)	Very High (e.g., Beef: up to 18x more land than plant protein; 77% of agricultural land for livestock)	Very High (e.g., Beef: ~15,500 liters/kg)	Significant contributor to deforestation, land degradation, water eutrophication, and biodiversity loss. Accounts for ~14.5–20% of global GHG emissions.	Poore & Nemecek, 2018; Santo et al., 2020; Onwezen et al., 2021; Silva & Conte-Junior, 2024; Search results
Plant-Based Proteins	Low (e.g., Soy: ~0.58 kg CO ₂ -eq/kg, 95% reduction vs. beef)	Significantly Lower (up to 18x less land than animal protein)	Significantly Lower (e.g., Lentils: ~1,250 liters/kg)	Contribute to soil fertility, reduce need for synthetic fertilizers, lower methane and nitrous oxide emissions, reduce habitat loss, preserve ecosystems.	Poore & Nemecek, 2018; Santo et al., 2020; Tso & Forde, 2021; Langyan et al., 2022
Microbial Proteins	Favorable sustainability profile (0.79 kg CO ₂ -eq/kg to 6.15 kg CO ₂ -eq/kg for mycoprotein and products from search results)	Limited land area required	(Generally low due to controlled cultivation)	High protein yields per unit area, can utilize industrial byproducts for waste valorization. Challenges with public and regulatory acceptance.	Sawant et al., 2025; Muys et al., 2023; Alves et al., 2023; Search results
Algal Proteins	Significantly reduced environmental footprint because its cultivation requires much less water and land	Significantly lower resource inputs compared to traditional agriculture	Significantly lower resource inputs compared to traditional agriculture	High digestibility, comparable amino acid profiles to conventional sources. Easier/more cost-effective harvesting for filamentous algae.	Smetana et al., 2015a; Bahraseman et al., 2025; Rahaman et al., 2025; Ijaola et al.,

					2024; Leong et al., 2024
Insect-Based Proteins	Comparatively low resource requirements (e.g., mealworm protein reduces GHG by 10-100x vs. beef from search results)	Comparatively low resource requirements	Comparatively low resource requirements (e.g., 1 liter water/kg protein from search results)	Elevated protein content, rapid life cycles, contribute to waste management. Faces challenges with consumer acceptance and regulatory frameworks.	Smetana et al., 2015b; Abro et al., 2025; Queiroz et al., 2023; Search results
Cultured Meat	Potential for substantial reduction (up to two orders of magnitude reduction in GHG emissions)	Potential for substantial reduction (up to two orders of magnitude reduction in land use)	Potential for substantial reduction (up to two orders of magnitude reduction in water consumption)	Mimics organoleptic properties of conventional meat. Challenges related to production costs, scalability, and consumer perception; requires development of sustainable culture media.	Hochedlinger & Zepeda, 2023; Fatima et al., 2023; Samad et al., 2024; Nunes et al., 2025; Choi et al., 2025

3. CONSUMER ACCEPTANCE AND FUTURE DIRECTIONS

A study provided new insights into consumer attitudes toward different protein products and factors associated with the acceptance of cultured chicken and beef. Beliefs about plant-based meat alternatives were more positive than those about cultured meat, with plant-based products viewed most favorably across all traits except animal welfare and environmental friendliness (Padilha et al., 2022). Despite generally negative belief scores for cultured meat, about a quarter of consumers still expressed willingness to consume cultured chicken and beef (Padilha et al., 2022). Another study reported that vegetarians, men, younger individuals, and those with higher education tended to have stronger preferences for plant-based and laboratory-grown alternatives over farm-raised beef (Loo et al., 2020). A separate survey revealed that 66.2% of respondents were open to incorporating plant-based sources into their diet, while 23.1% were willing to eat insect-derived food, and 21% were open to cultured meat (Stubelj et al., 2025). Acceptance

of these alternative protein sources was influenced by demographic factors, familiarity, frequency of meat consumption, and intention to reduce future meat consumption. Men and individuals who had previously tried insect-based foods were more favorable toward consuming insect-based foods and cultured meat. Regression analysis showed that higher levels of food technology neophobia and avoidance of eating insects correlated with lower interest in trying cultured meat. Women, in particular, showed less interest in experimenting with cultured meat (Stubelj et al., 2025).

To enhance the quality of cultivated meat, numerous production parameters must be considered, including stem cells, suitable scaffold materials, increased muscle tissue cells with actomyosin, and genetic modification. Furthermore, replacing packaging materials with emerging technologies and utilizing by-products or bio-based materials can create sustainable packaging for cultivated meats. Finally, transparency in labeling is crucial to mitigating the risk of food neophobia associated with cultivated meat (Adi et al., 2024). In

response to increasing consumer demand for sustainable and plant-based food options, sunflower flour, a byproduct of oil extraction, is emerging as a promising protein source. While further improvements are needed to optimize flavor, studies highlight the potential of sunflower meal to contribute to a more sustainable food system and offer consumers a nutritious and appealing plant-based protein alternative (Andrade et al., 2025).

Blue food-based alternative proteins offer a potential solution to address food shortages and promote sustainability. The extraction of algal proteins and the use of cell-cultured seafood production can overcome regional limitations and provide essential amino acids, polyunsaturated fatty acids, vitamin B12, and minerals in a safer and more environmentally friendly manner. While laboratory-grown meat and seafood show promise as emerging technologies, they are still in early stages and face significant technical challenges. These emerging technologies are poised to further advance the development of alternative proteins from aquatic sources, providing more possibilities for sustainable food production and healthier dietary choices (Li et al., 2024). Ongoing research focused on the efficient extraction, processing, and formulation of proteins from these diverse sources, coupled with targeted regulatory developments and consumer education initiatives, is expected to facilitate the acceptance and widespread integration of sustainable protein sources into future food systems.

4. OVERVIEW OF CURRENT GLOBAL PROTEIN SOURCES

The increasing popularity of plant-based proteins stems from growing public awareness of environmental and ethical issues (Rashwan et al., 2023; Langyan et al., 2022; Hertzler et al., 2020). These alternatives offer various health advantages and fit well within a balanced diet.

As consumers become more conscious of health, climate change, and animal welfare, they are increasingly motivated to shift from meat towards alternative protein sources (Rashwan et al., 2023). Many plant-based proteins can provide a greater array of essential nutrients while also being more sustainable for the environment. Legumes and pulses, such as lentils, chickpeas, black beans, and peas, are highly efficient protein producers globally and are also good sources of dietary fiber, iron, and folate (Langyan et al., 2022). Soy, found in tofu, tempeh, and soy milk, is unique among plant proteins as it contains all the essential amino acids that humans must obtain from their diet. Plant-based protein intake also includes whole grains like quinoa (a complete protein), brown rice, and oats (Langyan et al., 2022; Hertzler et al., 2020). Nuts and seeds, such as almonds, walnuts, chia seeds, flaxseeds, and hemp seeds, are excellent sources of protein, healthy fats, antioxidants, and omega-3 fatty acids. Fungi, like *Fusarium venenatum*, are used to produce mycoprotein on a large scale for meat alternative products, while fermenting plant proteins can improve how well we digest and absorb their nutrients. Microalgae, such as spirulina and chlorella, contain around 70% protein and are also rich in vitamins and minerals. Pea and fava bean proteins are commonly used in plant-based meat substitutes (Rashwan et al., 2023). Ongoing research and advancements in plant-based proteins are crucial for ensuring sustainable and nutritious food options.

Proteins are essential macronutrients vital for human health, supporting muscle growth, tissue repair, enzyme function, and immune system activity. They primarily come from two main sources: animal-based and plant-based foods (Du et al., 2025). Animal-derived proteins (found in meat, poultry, fish, dairy, and eggs) are known as complete proteins because they supply all the essential amino acids in the right proportions for human needs (Medina-Vera et al., 2024). While meat products (beef, pork, and

poultry) are high in protein and micronutrients like iron, zinc, and

vitamin B12 per gram, they also tend to be high in saturated fat and cholesterol, which can be linked to heart health issues (Singh et al., 2025). Fish and seafood, with their high-quality protein and beneficial omega-3 fatty acids, are often a healthier choice compared to red meats (Akyüz et al., 2024). Dairy products, including milk, cheese, and yogurt, contain casein and whey proteins that are easily absorbed and used by the body, and they are frequently included in supplements for building muscle (Tarahi, 2024). Eggs, for example, are considered a initial protein due to their balanced amino acid composition and high bioavailability (Chib et al., 2024).

Despite being a complete form of nutrition, producing animal proteins has significant environmental consequences, including greenhouse gas emissions, excessive water usage, and ethical concerns about industrial farming practices. These issues have driven the increasing adoption of plant-based proteins as more sustainable alternatives (Aparna & Kata, 2024). Plant-based protein sources include legumes, cereals, oilseeds, tubers, and green leafy vegetables, offering a more environmentally friendly way to meet our protein requirements (Du et al., 2025). However, some individual plant proteins may lack one or more essential amino acids, so they need to be eaten in combination with other sources to create a complete protein profile (Singh et al., 2025). Among plant-based protein sources, legumes are particularly important, with soybeans, peas, chickpeas, lentils, and beans containing between 18% and 50% protein (Akyüz et al., 2024). Due to its good amino acid profile and versatility in food, soy protein is widely used in plant-based dairy and meat alternatives (Medina-Vera et al., 2024). Pea protein is becoming more popular as a highly digestible and less allergenic option, while common legumes like chickpeas and

lentils provide quality protein along with dietary fiber, which supports healthy digestion and energy balance (Chib et al., 2024).

Cereals and pseudocereals provide some plant-based protein, although generally less than legumes. Common cereals like wheat, rice, corn, and barley have moderate protein content (6%-15%), with wheat's gluten being widely used in food processing (Aparna & Kata, 2024). Pseudocereals, including quinoa, amaranth, and buckwheat, are notable for having a complete amino acid profile similar to animal proteins, making them valuable dietary components in vegetarian and vegan diets (Du et al., 2025). Among oilseeds, sunflower, flaxseed, chia, and hemp seeds contain 25%-35% protein and also provide healthy fats, antioxidants, and other beneficial compounds (Akyüz et al., 2024). Almonds, walnuts, and peanuts are moderate sources of protein and also offer essential fatty acids, fiber, and vitamins, making them nutrient-dense foods (Singh et al., 2025). Tubers and leafy greens also contain plant proteins but at lower levels than legumes and cereals. Potato, yam, and cassava, which are starchy vegetables with relatively low protein content, are being studied as potential sources for protein extraction technologies (Tarahi, 2024). Studies have shown that leafy greens, such as spinach, moringa, and alfalfa, can provide some protein and also contain beneficial bioactive compounds, making them an area of growing interest in plant-based nutrition (Medina-Vera et al., 2024). Plant proteins are generally less easily digested than animal proteins, but food processing techniques like fermentation, enzymatic breakdown, and protein isolation have helped to improve their nutritional properties and how they can be used in foods (Chib et al., 2024).

Conventional protein sources typically offer near-complete amino acid profiles, with generally higher bioavailability. In contrast, plant-based proteins, being rich in dietary fiber, low in saturated fats, and containing antioxidant

compounds, are often considered beneficial for cardiovascular health (Langyan et al., 2022). However, given that individual plant proteins may have lower levels of certain essential amino acids, strategic combination of different plant protein sources (e.g., pairing legumes with grains) is crucial to ensure a complete intake of all essential amino acids (Hertzler et al., 2020). With the global demand for protein increasing and concerns about sustainability growing, research has focused on new protein sources and new ways to use them in food (Aparna & Kata, 2024). Sustainable protein is a crucial area for the food industry, including plant-based alternatives, alternative meat products, protein-enriched foods, and new methods for extracting protein (Singh et al., 2025). Innovations like precision fermentation and cellular agriculture aim to provide sustainable protein sources that are more efficient and have a lower environmental impact (Akyüz et al., 2024). Due to the increasing popularity of plant-based diets, more research is needed to improve plant protein formulations, increase how well they are digested, and ensure that consumers accept these alternative protein products (Medina-Vera et al., 2024). In summary, proteins are vital macronutrients from various sources, each with its own advantages and disadvantages. While animal proteins are nutritionally valuable, their environmental impact has led to a greater interest in plant-based proteins. Protein can come from legumes, cereals, oilseeds, and other plant sources, and processing methods have been improved to enhance the nutritional quality of plant proteins. As we look to the future of protein consumption, which will likely involve a combination of traditional and alternative proteins for sustainability, nutrition, and consumer preferences, further studies assessing their overall contribution to protein quality are important (Du et al., 2025).

5. CURRENT INNOVATIONS IN PLANT-BASED PROTEIN TECHNOLOGY

The global movement towards sustainable protein solutions has catalyzed significant advancements in plant-based protein technology. Central to this progress are innovative food-processing techniques designed to enhance the texture, functionality, and sensory attributes of plant proteins, thereby increasing their competitiveness with conventional animal-based products. Techniques such as extrusion, fermentation, and enzymatic hydrolysis are key methodologies employed to improve protein structure, palatability, and bioavailability (Tachie et al., 2023; Garcia Arteaga et al., 2022). These processes have facilitated the development of novel plant-based food systems that more closely mimic the sensory properties of animal proteins, contributing to greater consumer acceptance (Hefferon et al., 2023).

Extrusion technology has been particularly effective in transforming plant protein structures into fibrous, meat-like textures. High-moisture extrusion is notable for its ability to yield products with enhanced elasticity and chewiness, critical characteristics for plant-based meat analogs (Wang et al., 2022). Nevertheless, ongoing challenges include optimizing flavor profiles and ensuring favorable ingredient interactions, necessitating further refinement of processing parameters and formulations. Fermentation, a process leveraging microbial activity, represents another promising avenue for improving both the flavor and nutritional value of plant proteins. For instance, the application of lactic acid bacteria and fungal cultures can mitigate undesirable flavors and enhance protein digestibility (Garcia Arteaga et al., 2022), resulting in more palatable and nutritious plant-based alternatives to animal-derived foods. Additionally, enzymatic hydrolysis has been investigated as a method to break down complex protein structures into

peptides with improved solubility, emulsification, and overall functional properties (Garcia Arteaga et al., 2022). This approach has proven particularly useful in the development of dairy and egg analogs, where modified protein interactions are essential for achieving desired texture (Wang et al., 2022).

Beyond processing innovations, the market has seen a rise in new products that closely mimic animal-based foods, aligning with consumer preferences. By combining flavor chemistry with extrusion processing, companies such as Beyond Meat and Impossible Foods have successfully developed meat analogs that replicate the texture and juiciness of conventional meats (Tachie et al., 2023). Similarly, plant-based dairy and egg substitutes have benefited from breakthroughs in protein formulation, enabling the production of milk alternatives with superior frothing capabilities and cheeses that melt and stretch effectively. These product advancements have played a significant role in increasing market acceptance and consumer interest in plant-based diets (Tziva et al., 2023).

Innovative approaches are also leading to the creation of novel plant protein varieties, including hybrid protein systems that combine plant-derived and microbial-based proteins. These hybrid systems aim to balance nutritional and sensory characteristics while maintaining sustainability (Lurie-Luke, 2024). Furthermore, fungal-derived proteins, such as mycoprotein, have demonstrated unique textural properties, addressing the need for diverse alternative protein sources (Ismail et al., 2020). While research indicates that insect-based proteins offer high digestibility and a lower environmental impact, their widespread adoption has been limited by cultural and regulatory barriers (Tziva et al., 2023). The future of plant-based protein technology will heavily rely on research and development to enhance processing efficiency, expand the range of ingredient sources, and overcome the

sensory limitations of current products. Emerging food processing techniques, including precision fermentation and cellular agriculture, hold revolutionary potential, contingent upon sustained investment in their development (Lurie-Luke, 2024). Consumer education and supportive policy frameworks are crucial for promoting the acceptance and adoption of these innovations (Tziva et al., 2023).

Ultimately, the future of food lies in sustainability, and the technological advancements in plant-based proteins can provide a viable solution to mitigate environmental impact, enhance food security, and facilitate the transition towards healthier dietary patterns.

6. CONSUMER ACCEPTANCE AND UTILIZATION OF PLANT-BASED PROTEINS: CHALLENGES

Replicating the sensory attributes of animal products like taste, texture, and appearance is a major technical challenge due to the inherent differences between plant and animal proteins (Siddiqui et al., 2022; Bohrer, 2019). These discrepancies can deter consumers. Extending the shelf life of plant-based ingredients is also crucial, as they are prone to spoilage (Kyriakopoulou et al., 2021). Manufacturers are addressing this by using antioxidants to prevent rancidity and organic acids and phosphates for better shelf stability (Siddiqui et al., 2022). Also, consumer perception is vital. Cultural norms, ingrained mindsets, and familiarity with traditional meat-heavy diets hinder the acceptance of plant-based options (Michel et al., 2021; Hartmann and Siegrist, 2020). Consumers often worry about plant-based products falling short in taste and texture compared to meat, and the perceived pleasure of meat consumption also plays a role (Apostolidis & McLeay, 2016). Additionally, issues like allergen concerns, processing

techniques, and nutritional quality need to be addressed (Jareonsin et al., 2024). Overcoming these perceptions requires comprehensive consumer education and improved access to plant-based food resources, especially in lower-income communities (Michel et al., 2021).

Economic factors significantly impact the availability and consumer interest in plant-based

proteins. The specialized ingredients and processing often lead to higher production costs, making plant-based alternatives more expensive than traditional meat products (Aschemann-Witzel et al., 2021). This price difference is a major barrier to wider adoption, and limited production volumes further restrict market presence (Tziva et al., 2020). Reducing processing costs through research and development is crucial for making plant-based protein production more economically viable (Aschemann-Witzel et al., 2021). Combining plant-based proteins with algae-based proteins offers a promising solution to improve properties and better mimic meat, contributing to sustainability (Jareonsin et al., 2024). Algal proteins have significant potential in various industries, though broader adoption requires continuous innovation (Dewan et al., 2025). Supply and demand dynamics, along with existing policies, greatly influence plant-based protein consumption. Government subsidies favoring livestock farming can limit the competitiveness of alternative proteins (Springmann et al., 2018). The adoption of plant-based nutrition, a relatively recent trend, is heavily influenced by social trends and consumer demand for sustainable consumption (Mancini & Antonioli, 2022). Encouraging policy changes, such as subsidies for research and development in plant-based proteins, can create a more favorable environment (Springmann et al., 2018). A coordinated effort among industry, policymakers, and consumers is essential to promote the development and

adoption of high-quality and cost-competitive plant-based proteins (Springmann et al., 2018).

7. STRATEGIC DIRECTIONS AND FUTURE RECOMMENDATIONS

7.1 Worldwide Impact

The ongoing global transition towards plant-based proteins presents a significant opportunity to foster a healthier populace with heightened awareness of sustainable solutions addressing

critical challenges such as climate change, food security, and human health. Traditional livestock farming has been a major contributor to greenhouse gas emissions, deforestation, and biodiversity loss. Deliberate shifts away from this pattern can help mitigate these issues by reducing emissions and conserving vital land and water resources (Springmann et al., 2018). Plant-based proteins offer an efficient pathway to enhance food security, requiring fewer inputs to produce essential nutrients for the global population. Notably, plant-based protein production exhibits a higher protein yield per hectare compared to livestock farming, thus better addressing the needs of an ever-growing population (Piercy et al., 2022). Furthermore, the effective integration of plant-based proteins into the global food system has the potential to reduce the prevalence of chronic diseases such as cardiovascular ailments and obesity-related risks (Eilam et al., 2023).

7.2 Upcoming Developments

Emerging technologies such as cultured and algae-based proteins are poised to become significant contributors to sustainable and affordable protein sources. Algae, particularly microalgae, are rich in essential amino acids, vitamins, and bioactive compounds, positioning them as highly nutritious and sustainable protein sources. Algae production does not necessitate arable land and can be cultivated in controlled indoor environments with low water

and nutrient inputs, offering an effective solution for regions with agricultural limitations (Eilam et al., 2023). Recent advancements in biotechnology have facilitated the production of cultured meats that closely mimic the sensory and nutritional characteristics of traditional meat, thereby reducing associated environmental burdens. Utilizing cellular agriculture, scientists cultivate meat directly from animal cells in bioreactors, bypassing traditional livestock farming and its adverse environmental effects (Alam et al., 2024). Moreover, the incorporation of microalgae into cultured meat systems holds the potential to further enhance the sustainability of cultured meat proteins by enriching the nutrient density of the growth substrate, increasing production efficiency, and reducing costs (Todhunter et al., 2024).

7.3 Research and Development (R&D) Recommendations

Targeted research and development initiatives are essential to propel the advancement of the plant-based protein industry. A key focus should be on enhancing the sensory properties of plant-based proteins, as taste, texture, and aroma are critical determinants of consumer acceptance. Alternative processing strategies, including high-moisture extrusion, enzymatic hydrolysis, and fermentation, are being investigated to improve the functional properties of plant-based proteins and develop more meat-like textures (Piercy et al., 2022). Furthermore, exploring underutilized crops, such as various pulses and duckweed, as sustainable protein sources would diversify healthy food options available to consumers (Eilam et al., 2023). R&D efforts should also prioritize improving the bioavailability of plant-based proteins by addressing digestibility and amino acid completeness issues. Fortification with micronutrients and amino acid balancing techniques can make plant-based alternatives more suitable for diverse dietary needs across different societies (Todhunter et al., 2024).

7.4 Policy Proposals

Government policies play a crucial role in incentivizing the adoption and growth of plant-based proteins. Implementing subsidies and financial incentives specifically targeting plant-based protein R&D and production is a potent policy lever. Redirecting agricultural subsidies away from livestock farming towards sustainable protein alternatives can ensure governments foster a more equitable and resilient food system (Springmann et al., 2018). Policy support for the establishment of plant-based food processing facilities, as a means to develop a new market and enhance accessibility, will also amplify these effects. Similarly, public procurement policies hold significant potential in normalizing plant-based consumption. The increased inclusion of plant-based alternatives in meal programs within institutions such as schools, hospitals, and government offices can promote wider acceptance of these food products among the consumer population (Piercy et al., 2022). Additionally, regulatory frameworks need to ensure transparency in labeling and nutritional claims to prevent misleading marketing practices and enable consumers to make informed choices regarding plant-based products (Alam et al., 2024).

7.5 Market Expansion Strategies

Expanding the market reach of plant-based proteins necessitates comprehensive consumer education and strategic collaborations across industries. For instance, public health campaigns emphasizing the health and environmental benefits of plant-based diets can be an effective approach. Clear and science-based messaging can address consumer skepticism and encourage greater adoption of plant-based eating patterns (Eilam et al., 2023). Furthermore, partnerships between plant-based food producers and traditional food industry players can enhance consumer education about the benefits of these foods, contribute to product innovation, improve

distribution channels, and increase the affordability of plant-based options. The increasing inclusion of plant-based options on menus and in product lines by major fast-food chains and grocery stores, for example, can contribute to the normalization of plant-based consumption among mainstream populations (Todhunter et al., 2024). Indeed, advancements in food technology, including 3D food printing and precision fermentation, are creating novel pathways to produce high-quality plant-based foods at scale while preserving nutritional qualities and taste (Alam et al., 2024).

7.6 Successful Models and Case Illustrations

The increasing adoption of plant-based proteins has been significantly facilitated by innovations in food technology, growing consumer demand for sustainable alternatives, and supportive government policies worldwide. Numerous examples across the globe and within specific regions illustrate how plant-based proteins are contributing to solutions for environmental, economic, health, and other pressing issues. Products developed by companies like Beyond Meat and Impossible Foods have revolutionized the plant-based food market by creating options that closely mimic the sensory and cooking performance of traditional meat. These companies employ sophisticated processing methods, including high-moisture extrusion and heme protein fermentation, to enhance the palatability of plant-derived alternatives. The production of these plant-based meat substitutes results in lower greenhouse gas emissions compared to livestock farming (Kyriakopoulou et al., 2024) and requires less water than traditional meat production (Crowley et al., 2022). Furthermore, the large-scale adoption of such alternatives can help curb intensive animal agriculture, mitigating deforestation and biodiversity loss while establishing a more sustainable means of meeting global protein demand (Springmann et al., 2018).

Several countries have emerged as leaders in promoting plant-based diets through policy and agricultural innovation. The Netherlands, for instance, has made substantial investments in alternative protein research, positioning itself as a frontrunner in sustainable food production. The Dutch government has funded projects aimed at enhancing the nutritional quality of plant-based proteins and improving consumer acceptance through targeted information campaigns (Rojas Conzuelo et al., 2022). Similarly, Canada has made significant investments in its pulse-based

protein sectors, recognizing the environmental and economic advantages of expanding plant-based food markets. The Canadian government's Protein Industries Supercluster Initiative has propelled research into innovative plant proteins with enhanced functional properties and market viability (Kumar et al., 2021). Community-based initiatives also highlight the potential impact of plant-based diets on health and environmental sustainability at the local level. Cities like Los Angeles and Berlin have implemented public initiatives to promote plant-based eating, including meat-free school meal programs and subsidies for plant-based restaurants (Kyriakopoulou et al., 2024). These initiatives are designed to enhance the appeal of plant-based dishes and encourage healthier eating habits. Research suggests that transitioning school meal programs towards plant-based foods can significantly reduce students' carbon footprints without compromising nutritional adequacy (Springmann et al., 2018). Moreover, plant-based diets have been linked to a reduction in cardiovascular diseases and obesity (Rojas Conzuelo et al., 2022), underscoring the importance of policies that promote these dietary patterns. In conclusion, a substantial body of studies and research underscores the potential benefits of plant-based proteins for the environment, human health, and food security. Innovations in research, policy, market

strategies, and product development play a crucial role in expanding plant-based food systems and ensuring their long-term sustainability.

8. CONCLUSION

The escalating global demand for protein, coupled with mounting environmental and ethical concerns associated with conventional animal agriculture, clearly highlights the critical need for sustainable alternative protein sources. This comprehensive review has underscored the diverse landscape of emerging protein options, including plant-based proteins from legumes and various starches, as well as novel sources such as microbial biomass, algae, insects, and cultured meat. Technological advancements in extraction, processing, and formulation are continuously improving the quality, functionality, and palatability of these alternatives, making them increasingly competitive with traditional animal proteins. This study has filled a significant gap in the existing literature by providing a strategic roadmap and future projections. By presenting the global impacts, future developments, R&D recommendations, policy proposals, market expansion strategies, and successful implementation models of plant-based proteins from an integrated perspective, it offers an original and practical contribution to the field. Specifically, its core original value lies in detailing not just the potential benefits of these proteins, but also the concrete steps and actions necessary for their successful integration into the global food system. While significant progress has been made, challenges remain, particularly concerning consumer acceptance, scalability of production, and regulatory frameworks. Overcoming these hurdles will necessitate continued interdisciplinary research to optimize protein profiles, enhance sensory attributes, and improve cost-effectiveness. Concurrently, supportive policies and comprehensive

consumer education initiatives are crucial to fostering broader public acceptance and facilitating the seamless integration of these sustainable proteins into global food systems. The future of protein consumption will likely involve a synergistic combination of traditional and alternative sources, driven by a collective commitment to sustainability, nutritional security, and evolving consumer preferences. Further research into the overall contribution of these alternative proteins to dietary quality and their long-term environmental impacts is essential to guide a sustainable and resilient global food supply. Briefly, this comprehensive analysis provides a roadmap to accelerate the transition to sustainable proteins and ensure future food security.

DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FUNDING

None.

ACKNOWLEDGEMENT

None.

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