***Review Article***

Sustainable Protein Alternatives: Exploring Plant-Based, Microbial and Novel Protein Sources

**Abstract**

Population growth, changes in diets and sustainability issues support the global demand for protein. Animal-based protein sources are responsible for substantial amounts of greenhouse gas emissions, deforestation and water wastage, urging the assessment of sustainable alternatives. Plant proteins, extracted from soy, peas, lentils and other legumes, have a smaller carbon footprint and health advantages less saturated fat and cholesterol. Laboratories are creating proteins from microbes, algae and insects and lab-grown meat, with all sorts of pros and cons about each medication. Screens have been developed for alternative proteins like corn starch, wheat starch, pea starch, potato starch, etc. Machines such as high moisture extruders, fermenters and extractors have developed and improved their capabilities, which has decreased their cost over time. The system cost is increased, but the product quality, functionality and palatability have improved, making it comparable to animal-based sources. But challenges remain in the form of consumer acceptance, expensive manufacturing processes and regulatory complexities that continue to slow their mass-production implementation. Combating these challenges may take multiple forms, from researching better protein in terms of quality and digestibility, to policy changes that promote new protein marketplaces, to consumer education around environmentally and health beneficial protein selections. To fulfil the nutrition needs of a global population in an ecologically-friendly manner moving forward, the food systems will need to include plant-based and novel sources of protein. For those who hear of alternative proteins and think it is a far-off trend over the horizon, an insufficient presence to solve large-scale hunger and climate challenges, think again. The current study examines the options, advantages and drawbacks of alternative proteins, a field that requires ongoing investigation and policy framing to help define the course of the global nutrition narrative.

**Key Words-** Plant-Based Proteins, Protein Quality, Amino Acid Profile, Sustainability, Meat Analogues

INTRODUCTION

People are becoming increasingly aware of their need for protein due to growth in population, changes in diets, and an increase in information about health and sustainability. Animal based proteins even though they are, traditional contribute to critical environmental problems such as greenhouse gas emissions, deforestation, as well as excessive use of land and water (Poore, J., & Nemecek T.,2018).

As a result, protein substitutes have emerged which reduce environmental impacts thereby ensuring food security and necessary nutrition (Poore, J., & Nemecek T.,2018). The plant-based proteins are the most researched sustainable protein substitutes. Plant -based proteins such as soy, peas, lentils and other legumes provide various benefits, namely low saturated fats and zero cholesterol.

New developments in protein extraction and processing techniques for plant sources have improved the functional and sensory properties of these proteins thereby improving user acceptance (Sawant etal.,2025). There has been a promising development in the culinary application of plant- derived proteins with the onset of plant -derived materials and edible films. Moreover, it is being extensively studied to replace animal proteins with plant-based protein isolates and concentrates in food formulations without changing the preferred texture and flavour (Onwezen et al.,2021).

Alternative sources such as microbials, algae and insects also have potential to become sustainable proteins options apart from plant-based proteins. Sources of microbial protein such as fungi, yeast and bacteria have shown to have high protein yield and sustainability (Sawant et al., 2025). They are processed from a new generation of Quorn-like proteins that can be grown in a small area and by using industrial byproducts thereby reducing the waste produced. Similarly, algal proteins (spirulina and chlorella) also have comparable amounts of amino acids and high digestibility properties (Smetana et al.,2015). Algae farming requires far less resources than traditional crops making it a vanguard of sustainable protein resources.

Insect- based proteins are another interesting protein replacement as it contains high protein content, develops at a rapid rate and needs less resources. Edible insects such as mealworms and crickets are both nutritious and can be added to a wide range of food products including snacks and protein bars. Insect-based proteins face major hurdles as consumers have limited acceptance and regulatory frameworks are not feasible (Van Huis, 2013).

Another sustainable protein substitute is cultured meat also called cell based or lab -grown meat. During this process an animal cell is cultured in a controlled environment hence allowing meat to be manufactured without relying on traditional animal husbandry methods. This method apart from providing protein that feels and tastes like meat can reduce greenhouse emissions, land use and water consumption, reductions can reach up to 100 times (Hochedlinger, R., &Zepeda, M.,2023). However, challenges related to cost, scalability and user perception must be addressed before this technology can flourish on a broader scale.

Consumer’s perceptions of sustainable protein alternatives are decisive factor determining their commercial performance. Taste, texture, price and nutritional advantages all affect switching to alternate protein sources. Furthermore, as people become more aware of the ethical and environmental concerns related to traditional animal agriculture, the market for plant-based and alternative proteins is growing (Onwezen et al., 2021)

OVERVIEW OF PROTEIN SOURCES

**Alternative protein sources:** Sustainable protein alternatives are critical to overcoming global food sustainability challenges and mitigating environmental degradation (Onwezen et al., 2021). Traditional sources of protein are mainly of animal origin, including meat, poultry, fish, seafood, dairy and eggs, but the increasing demand for more sustainable sources of protein has led to research into alternative protein sources. Meat and poultry (beef, pork, chicken, turkey) are high biological value (HBV) protein, readily absorbable proteins that are also rich in essential amino acids, iron and B vitamins. Fish like salmon, mackerel and tuna which not only provide quality protein but are also rich in omega-3 fatty acids, and shellfish (shrimp, oysters) provide important minerals like zinc and selenium. Dairy foods like milk, cheese, yogurt which provide complete proteins and calcium and probiotics and whey and casein are frequently used as supplements. Eggs, which is exceptionally bioavailable, contain all nine essential amino acids and include choline, good for the brain. Crickets and mealworms are examples of edible insects identified among new sustainable protein sources due to their high protein content, healthy fats and micronutrients (Smetana et al., 2015). Research into the extraction, processing and formulation of these proteins along with specific regulatory and consumer education efforts is expected to facilitate the acceptance and widespread use of sustainable protein sources in the future.

**Table 1: Specific Proteins in Various Plant and Animal Sources**

| **Source** | **Key Proteins** | **Protein Content** | **Additional Notes** | **References** |
| --- | --- | --- | --- | --- |
| **Soybean** | Glycinin, Conglycinin | 36-56% of dry weight 29g per cup of boiled soybeans | Glycinin and conglycinin make up 80% of total protein | Tarahi (2024)​ |
| **Pea** | Legumin, Vicilin, Convicilin | 20-30% protein content | Used in plant-based protein isolates for hypoallergenic properties | Singh et al. (2025)​ |
| **Chickpea** | Albumins, Globulins | 17-22% of total seed weight | High lysine content but low sulfur-containing amino acids | Aparna & Kata (2024)​ |
| **Lentil** | Globulin, Albumin, Prolamin | 24-31% protein content | Rich in iron and fiber, widely used in plant-based diets | Du et al. (2025)​ |
| **Mung Bean** | 8S and 11S Globulins | 20-32% protein content | High gelling and emulsifying properties, good for meat substitutes | Tarahi (2024)​ |
| **Quinoa** | Chenopodin | 12-18% protein content | A complete protein with all essential amino acids | Akyüz et al. (2024)​ |
| **Hemp Seed** | Edestin, Albumin | 25-35% protein content | High digestibility and rich in omega-3 fatty acids | Medina-Vera et al. (2024) |
| **Chick** | Actin, Myosin, Collagen | 27g protein per 100g | Lean protein source with lower fat content than beef | Chib et al. (2024) |
| **Fish**  | Myosin, Parvalbumin | 25g protein per 100g | Rich in omega-3 fatty acids and highly digestible protein | Tarahi (2024) |

PLANT BASED PROTEIN SOURCES

The popularity of plant-based proteins is increasing rapidly with growing environmental and ethical concerns (Rashwan et al., 2023; Langyan et al., 2022; Hertzler et al., 2020) and they offer different health benefits and are also ideal components of a well-balanced diet. Rising awareness for health, climate impact and animal welfare amongst consumers is encouraging them to make the move from meat towards alternative proteins (Rashwan et al., 2023). Many sources of plant-based protein can possess more essential nutrients while also being more environmentally sustainable. Legumes and pulses (lentils, chickpeas, black beans, peas) are one of the most productive sources of protein in the world and are also suitable dietary sources of dietary fibres, iron and folate (Langyan et al., 2022). Soy, derived from soybeans, tofu, tempeh and soy milk, is one of the few plant proteins that contain all of the essential amino acids that a human must consume from the diet. Plant protein intake also comes from whole grains such as quinoa, brown rice and oats, while quinoa is a complete protein (Langyan et al., 2022; Hertzler et al., 2020). A great source of protein as well as healthy fats, antioxidants and omega-3 fatty acids are nuts and seeds like almond, walnut, chia seeds, flaxseeds, hemp seeds. Fungi, such as *Fusarium venenatum*, are used for the large-scale production of mycoproteins for use in meat alternative products, whereas fermented plant proteins improve digestibility and nutrient absorption. Microalgae like spirulina and chlorella, around 70 percent protein, also have vitamins and minerals galore. Pea and fava bean proteins are some of the most widely used plant proteins in plant-based meat substitutes (Rashwan et al., 2023). continued research and Subsequent innovation in plant-based proteins are critical for ensuring sustainable and nutritious dietary choices.

Proteins are important macronutrients that are fundamental to human health in supporting muscle growth, tissue repair, enzyme function and immune system activity. They are mostly derived from two primary sources: animal-based and plant-based proteins (Du et al., 2025). Proteins from animal-derived foods (meat, poultry, fish, dairy, and eggs) are known as complete proteins since they provide all of the essential amino acid in proportions suitable for human nutrition (Medina-Vera et al., 2024). With many dietary proteins and micronutrients such as iron, zinc and vitamin B12 per gram, meat products (beef, pork, and poultry) are high in saturated fat and cholesterol, implicating them in cardiovascular health issues (Singh et al. 2025). For their high protein quality and excellent omega-3 fatty acids content, fish and seafood are a healthier choice than red meats (Akyüz et al., 2024). Dairy products, including milk, cheese and yogurt, contain casein and whey protein that are absorbed and utilized effectively and are commonly included in muscle-building supplements (Tarahi, 2024). Eggs are, for example, a "reference" protein because of their balanced amino acid composition and high bioavailability (Chib et al., 2024).

Despite being one of the most complete forms of nutrition, the production of animal proteins has major environmental impacts including greenhouse gas emissions, excess water usage and ethical considerations of industrial farming practices. Such concerns have driven the growing adoption of plant-based proteins as more sustainable alternatives (Aparna & Kata, 2024). The plant-based protein sources include legumes, cereals, oilseeds, tubers and green leaves and they are promising alternative sources of dietary protein that provide a greener pathway to meeting protein requirements (Du et al., 2025). However, several specific plant proteins are deficient in one or more essential amino acid(s) and therefore need to be combined with other sources in the diet to achieve a complete protein profile (Singh et al., 2025). When considering only plant-based protein sources, legumes play an important role, with soybeans, peas, chickpeas, lentils and beans having a protein content of between 18 and 50% (Akyüz et al, 2024). Due to its good amino acid profile and functional ability, soy protein is one of the most used ingredients in plant-based dairy and meat alternatives (Medina-Vera et al., 2024). Pea protein is becoming increasingly popular as a good digestible, hypoallergenic option, while globally consumed legumes such as chickpeas and lentils, provide quality protein with dietary fibre which supports healthy digestion and energy balance (Chib et al., 2024).

Cereals and pseudocereals provide some plant-based protein although they generally have a low protein content compared to legumes. Currently, conventional cereals like wheat, rice, corn, and barley range between moderate protein content (6%-15% accustomed to wheat's gluten, widely applicable in food processing (Aparna & Kata, 2024). Pseudocereals including quinoa, amaranth, and buckwheat are distinguished by a complete amino acid profile resembling animal proteins, thus serving as effective dietary elements in vegetarian and vegan diets (Du et al., 2025). Amongst oilseeds, sunflower, flaxseed, chia and hemp demonstrate 25%-35% protein and are also presented as healthy fats, antioxidants and bioactive compounds, which contributes to the overall health (Akyüz et al., 2024). Almonds, walnuts and peanuts are moderate sources of protein and provide essential fatty acids, fibres and vitamins and are therefore considered a nutrient-dense food (Singh et al., 2025).

Tubers and leafy greens are also a source of plant proteins but with lower levels than legumes and cereals. Potato, yam and cassava are starchy vegetables which have relatively low protein content and have been gaining attention as substrates to produce protein using the protein extraction technology (Tarahi, 2024). Studies have shown that leafy greens, such as spinach, moringa and alfalfa, may provide some protein and additionally be a source of bioactive characteristics thus making an area of growing interest in plant-based nutrition (Medina-Vera et al., 2024). Plant proteins generally had lower digestibility than animal proteins, but food processing technologies, including fermentation, enzymatic hydrolysis and protein isolation, had helped improve the nutritional properties of plant proteins and their functional applications (Chib et al., 2024).

With global demand for protein rising and sustainability concerns growing, research has focused on novel protein sources and novel food applications (Aparna & Kata, 2024). Sustainable protein is a critical area for the food industry and covers plant-based, alternative meat products, protein-enriched functional foods, and novel protein extraction methods (Singh et al. 2025). Novelties like precision fermentation and cellular agriculture were intended to provide sustainable protein sources with higher efficiency and lower environmental footprint (Akyüz et al., 2024). Due to the growing popularity of plant-based diets, more research is needed to improve plant protein formulations, boost digestibility rates and ensure consumer acceptance of such alternative protein products (Medina-Vera et al., 2024).

At a glance, proteins are vital macronutrients derived from various sources that come with their specific benefits and drawbacks. Although animal proteins are nutritionally valuable, their environmental impact has resulted in increased liking towards plant-based proteins. Protein can come from legumes, cereals, oilseeds and other plant sources as well, and processing methods have been refined to improve the nutritional quality of plant proteins. Studies which asses their overall contribution to protein quality are around the corner, as we enter the future of protein consumption, characterised by the combination of conventional with alternative proteins for sustainability, nutrition and consumer preferences (Du et al., 2025).

Table 2: Different protein alternatives with their sources and environmental befits (Ritala et al., 2017, Post 2012)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Protein Alternatives** | **Sources** | **Environmental Benefits** | **Challenges** | **Examples/Applications** |
| **Plant-Based Proteins** | Soy, Pea, Lentil, Chickpea | Lower greenhouse gas emissions, reduced land and water use compared to animal farming | Requires processing, potential allergenicity (e.g.- soy) | Beyond Meat, Impossible Foods, tofu, tempeh.  |
| **Algae-Based Proteins** | Microalgae (e.g.-Spirulina) | High yield per unit area, absorbs CO2, minimal water usage | Limited consumer acceptance, production scalability | Protein powders, supplements, snacks |
| **Insect Proteins** | Crickets, Mealworms, Black Soldier Flies | Low GHG emissions, high feed conversion efficiency, requires less land | Cultural acceptance, regulatory hurdles | Protein bars, flours, pet food |
| **Cultured (Lab-Grown) Meat** | Animal cell cultures | No animal slaughter, reduced land and water use, lower GHG emissions | High production costs, scalability, regulatory approval | Memphis Meats, Mosa Meat, lab-grown burgers |
| **Fungal Proteins** | Mycoprotein (e.g., Quorn) | Low environmental footprint, high protein content, grows on agricultural waste | Limited variety, requires fermentation infrastructure | Meat substitutes, nuggets, patties |
| **Single-Cell Proteins** | Bacteria, Yeast | Rapid growth, high protein yield, can use waste streams as feedstock | Consumer acceptance, requires bioreactors | Animal feed, potential human food products |
| **Seaweed Proteins** | Macroalgae (e.g., Kelp) | No freshwater or arable land required, absorbs CO2, supports marine ecosystems | Limited protein concentration, harvesting challenges | Snacks, supplements, plant-based seafood |
| **Legume-Based Proteins** | Lentils, Chickpeas, Beans | Nitrogen-fixing properties improve soil health, low water footprint | Requires processing, may cause digestive issues for some individuals | Hummus, falafel, plant-based meat alternatives |

Nutritional Comparison & advantages:Conventional protein sources generally provided almost complete amino acid profiles however, the bioavailability was much higher. Because plant proteins are rich in fibres, low in saturated fats and contain antioxidant compounds, they have been considered to be heart-healthy (Langyan et al., 2022). However, since plant proteins are often low in certain amino acids, combining plant proteins with help them pair as a partner high in certain amino acids (i.e., beans with rice) and provide a complete intake of amino acids (Hertzler et al., 2020).

KEY BENEFITS OF PLANT-BASED PROTEINS ON THE ENVIRONMENT

Plant-based proteins have a high comparative environmental advantage over traditional animal-derived proteins and are critical to fighting climate change, resource use, and loss of biodiversity. The food industry contributes significantly to greenhouse gas emissions (GHG), as livestock production represents about 14.5% of all emissions (Onwezen et al., 2021). Shifting towards plant-based proteins leads to significantly smaller carbon footprints because plants take less land, water and energy to maintain, as well as producing lower amounts of methane and nitrous oxide (Smetana et al., 2015). In order to preserve environmental equilibrium, a shift from animal to plant-based protein could be a necessity (Langyan et al., 2022).

Soy protein, which is one of the most common plant proteins produces -0.58 kg CO2-equivalent per kg product -this is a difference of over 95% in GHG emissions when compared with the production of 27 kg CO2-equivalent per kg product (referring to beef protein). Plant proteins such as peas, lentils, chickpeas and fava beans also sustain soil fertility, limiting the use of synthetic fertilizers with high carbon footprints. Plant protein is highly space-efficient, as one kilogram of plant protein can be produced using up to 18 times less area than one kilogram of the respective animal protein. The big savings comes from land use, because plant-based diets need a lot less land. Water use is also an important factor as it takes around 1,250 litres of water to produce a kilogram of lentils as opposed to around 15,500 litres for a kilogram of beef (Poore & Nemecek, 2018). So, this big cut in the amount of freshwater used can contribute to lessening water scarcity. The use of freshwater can be reduced by shifting to plant -based diets. Also, as there is a limited requirement for land clearing and habitat conversion in plant -based protein agriculture thereby reduced habitat loss and it in turn preserves ecosystems (Smetana et al., 2015).

Plant-based proteins have distinctive benefits as compared to animal -derived proteins as it combats biodiversity loss, climate change and resource depletion (Tso & Forde,2021). The livestock production contributes to 20% of the greenhouse gas (GHG) emissions globally (Santo et al., 2020), the food industry is one of the major contributors of GHG emissions. As plants require substantially less land, water and energy inputs and also emission of very low levels of methane and nitrous oxide, consumption of plant -based protein is associated with smaller environmental footprint (Santo et al.,2020). For example, beef protein generates around 27kg of CO2 while soy protein generates approximately 0.58kg of CO2 of product which is a reduction of 95% of GHG emissions (Santo et al.,2020). Plant proteins, peas, lentils, chickpeas and fava beans have low carbon footprints while animal proteins increase soil and decrease the need for synthetic fertilizers with large carbon footprints (Hertzler et al.,2020).

**Macro-nutrients for humans:** Proteins which help in growth of muscles, tissue repair, enzyme, immune system, etc. They can be derived from animal or plant-based proteins, which differ in nutrients and digestibility as well as sustainability aspects (Du et al., 2025), the two major sources of proteins. Animal-derived proteins (meat, poultry, fish, dairy and eggs) are complete proteins because they include all essential amino acids in proportions necessary for human nourishment (Medina-Vera et al., 2024). While protein and micronutrient dense foodstuffs (e.g., iron, zinc, and vitamin B12) (Singh et al., 2025), meat products (beef, pork, poultry etc) have also been demonstrated as high in saturated fat and cholesterol, pointing to overall cardiovascular health risk. Availability of fish and sea food with high protein quality and richest source of omega-3 fatty acids makes them the healthiest substitute of red meats (Akyüz et al., 2024). Casein and whey (bioavailable) proteins are found in dairy products (milk, cheese, and yogurt) and are commonly digested and used for nutritional supplements in muscle development (Tarahi, 2024). Eggs are also considered a reference protein because of their well-balanced amino acid profile and great bioavailability (Chib et al., 2024).

While proteins of animal origin are highly nutritious, their production leads to many environmental issues, such as greenhouse gas emissions, high water use and ethical issues with production methods applied in many industrial farms. Human dietary proteins are gradually shifting toward edible plant proteins as more sustainable options, catalysed by such apprehensions (Aparna & Kata, 2024). Plant proteins can be obtained from several sources, including legumes, cereals, oilseeds, tubers and leafy greens, providing an environmentally sustainable alternative for fulfilling dietary protein demands (Du et al., 2025). However, they are often deficient in one or more of these essential amino acids, which means that diets composed of solely plant-based sources require combinations from different vegetative sources to obtain a complete amino acid profile (Singh et al., 2025). Vegetables, nuts and legumes, primarily soybean, peas, chickpeas, lentils, and beans as an important source of dietary protein (Akyüz et al., 2024), constitute a major basis of protein-rich food products as plant-based protein sources with protein content ranges of 18% to 50%. Due to its optimal amino acid profile and functional characteristics, soy protein is widely applied in plant-based meat and dairy substitutes (Medina-Vera et al., 2024). Other sources of protein, like pea protein (due to its good digestibility and hypoallergenic properties) or nutrient-rich legumes like chickpeas and lentils, which are consumed worldwide and provide additional benefits like dietary fibres to help improve digestion, energy balance and satiety (Chib et al., 2024), have also become popular.

Gluten grains and pseudocereals additionally support utilisation of plant-based protein sources, but they compared to legumes provide a lower protein content. Representative cereals include wheat, rice, corn and barley, which can be of moderate protein content (6% to15%) and wheat gluten is extensively used for food processing (Aparna & Kata, 2024). Pseudocereals such as quinoa, amaranth and buckwheat emerge, as they provide a complete amino acid composition analogous to that of animal proteins, rendering them suitable for vegetarian and vegan diets (Du et al., 2025). When it comes to oilseeds, such as sunflower, flaxseed, chia and hemp, they contain 25% to 35% protein and are rich in healthy fats, antioxidants and bioactive compounds for improved overall well-being (Akyüz et al., 2024). Nuts like almonds, walnuts and peanuts are not high in protein, but they offer moderate protein alongside fatty acids, fibres and vitamins, representing a more nutrient-dense nutritional option (Singh et al., 2025).

Root vegetables and leafy greens, on the other hand, are alternative plant protein sources, but their protein content is lower than that of legumes and cereals. Potatoes, yams and cassava (or manioc) are starchy vegetables with low protein content that have also been increasingly studied for their potential use in protein extraction technology (Tarahi, 2024). Vegetables such as greens (e.g., spinach, moringa, alfalfa) also provide protein with bioactive properties and are an area of increasing interest within the plant-based nutrition space (Medina-Vera et al., 2024). Just as plant proteins are usually less digestible than animal proteins, there are related developments and technological advancements in food processing, including fermentation, enzymatic hydrolysis and protein isolation to enhance their nutritional and functional characteristics (Chib et al., 2024).

Research on new protein sources and food applications (Aparna & Kata, 2024) has been spurred on throughout the increasing global demand for protein along with sustainability issues. Due to rapid development in the food industry the current focal point is in areas such as meat alternatives, protein fortified functional foods and novel protein extraction techniques (Singh et al., 2025). This is where emerging technologies like precision fermentation and cellular agriculture come in play to develop sustainable protein that is more efficient and environmentally friendly (Akyüz et al., 2024). Because the plant-based diet continues to be popular, more investigation is needed to improve plant protein formulations and digestibility and enhance consumer acceptance of these alternative protein products (Medina-Vera et al., 2024).

To summarize, proteins are vital macronutrients you can receive from a variety of sources, each with their own pros and cons. Animal proteins provide high nutritional value, but their environmental impact has contributed to a growing interest in plant-based alternatives. Protein options available from legumes, cereals, oilseeds and other plant sources are potential viable protein sources whereby advances in processing methods can be employed to enhance their nutritional quality. It is projected that the future of protein consumption will be a mix of traditional and alternative protein sources, promoting the balance between sustainability, nutrition and consumer preferences (Du et al., 2025)

**Advances in Plant-Based Protein Technology**

Global shifts towards sustainable protein solutions have spurred rapid innovations in plant proteins technology. At the heart of this progress are new food-processing techniques that improve the texture, functionality and sensory appeal of plant proteins, making them more competitive with conventional animal-based products. Extrusion, fermentation and enzymatic hydrolysis are some of the main methods used to improve the structure and palatability, as well as the bioavailability of proteins (Tachie et al., 2023; Garcia Arteaga et al., 2022). These processes paved the way for the formation of newer plant-based food systems, in which the sensory properties of animal proteins are comparable, generating acceptance from consumers (Hefferon et al., 2023).

Most of the structures in plant proteins into fibrous, meat-like textures have been accomplished through extrusion technology. Among these, high-moisture extrusion is particularly effective in obtaining products with improved elasticity and chewiness, which are vital characteristics for plant-based meat analogues (Wang et al., 2022). Nevertheless, challenges still exist, including the need to optimize flavour and ensure that ingredients interact positively, so parameters need to be refined and formulations need to be refined. Fermentation a technique that uses microbiology to make junk food into health food is another promising approach for enhancing the flavour and the nutrition of plant proteins. For example, lactic acid bacteria and fungal cultures improve undesirable flavours and protein digestibility (Garcia Arteaga et al., 2022), offering palatable and nutritional plant-based foods compared to animal derived alternatives. In addition, enzymatic hydrolysis has been studied as a method to degrade protein structures into peptides with improved solubility, emulsification and functional properties in general (Garcia Arteaga et al., 2022). This approach has shown its usefulness especially in the development of dairy and egg gastronomic alternatives, where modified protein interactions are essential for desired (Gahukar et al., 2019) texture and mouthfeel (Wang et al., 2022).

In addition to processing innovations, new products that imitate animal-based food according to the consumers interests have risen. With the combination of flavour chemistry and extrusion processing companies like Beyond meat and Impossible foods have developed successful meat analogues that imitate the texture and juiciness of real meats (Tachie et al.,2023). Similarly, plant-based dairy and egg substitutes have benefitted from breakthroughs in protein formulation allowing for the manufacture of milk alternatives with superior frothing properties and cheese that melt and stretch. These products have played a significant role in increasing market acceptance and consumer interest in plant-based diets (Tziva et al.,2023).

New plant protein varieties are being created through innovative ways, with hybrid protein systems combining plant-derived proteins and microbial-based proteins. These hybrid varieties also create a balance between optimizing nutritional as well as sensory characteristics being sustainable. (Lurie-Luke,2024). Similarly, proteins that originate from fungi like mycoprotein showed unique textural characteristics fulfilling the need for alternative protein sources (Ismail et al.,2020). Although insect-based protein during research have been found to have high digestibility as well as lower environmental impact but it has been limited by the cultural and regulatory barriers (Tziva et al.,2023).

The future generations of plant -based technology will depend on R&D to improve the efficiency of processing, by widening the source of ingredients and by bringing out a solution for the sensory drawbacks of the current products. New food processing techniques that include precision fermentation and cellular agriculture could be revolutionary if we have a secured investment in developing them (Lurie-Luke,2024). Consumer education and policy support are the key to promote and accept these innovations (Tzivia et al.,2023). The future of food is in being sustainable, the technology behind plant -based protein can provide a solution for environmental impact, food security and helping people to transition to a healthier diet.

**Challenges in Adoption and Consumption**

The global transition to plant -based proteins is difficult with greater challenges, including technical, cultural, sensory, economic and regulatory issues. The acceptance for sensory attributes of animal-based products poses a technical challenge to replicate. As structure and composition of plant -based protein changes by nature, hence the change is taste, texture and appearance as compared to animal proteins (Siddiqui et al.,2022; Bohrer,2019). This can lead to unpleasant sensory experience leading consumers to completely avoid plant -based alternatives. Extended shelf life of plant-based raw materials is crucial as it may be prone to spoilage and quality reduction (Kyriakopoulou et al.,2021). Manufacturers are using various methods to lessen these challenges by adding antioxidants to minimize rancidity, along with the use of organic acids and phosphates to add shelf life (Siddiqui et al., 2022).

Consumer perception is of utmost importance when it comes to plant-based proteins. Cultural and Mindset barriers and a familiarity with traditional meat-based diets hinder acceptance of plant -based options (Michel etal.,2021; Hartmann &Siegrist,2020). One of the obstacles the consumers fear is that the plant-based products might not taste or feel as good as meat. With addition to this, Traditional practices and pleasure attached to eating meat also plays a crucial role in preventing them to shift from a plant-based diet (Apostolidis & McLeay,2016). The need for plant-based education with access to digital and food sources, especially to lower income communities are needed to change the perceptions and reach a wider range of consumers about plant-based diets (Michel et al.,2021).

Monetary elements play an important in the availability of the interest in plant-based proteins. As specialized ingredients and processing techniques are required for manufacturing these protein alternatives with high production costs, leading to higher retail prices than traditional meat products (Aschemannn-Witzel et al.,2021). This price gap is the biggest barrier preventing people from choosing plant -based products. Furthermore, limited production also restricts the market presence of these products (Tziva et al.,2020). Reduced costs related to processing with a further progress in research and development will increase the feasibility of plant-based protein production ( Aschemann-witzel et al.,2021).

Supply and demand factors along with policies determine the consumption of plant-based proteins. Government subsidies to livestock farming among other policies further limits alternative protein sources (Springmann et al.,2018). As adopting plant -based nutrition is a new trend among adults, it is largely influenced by social trends and consumer demands around sustainable consumption. (Mancini& Antonioli,2022), consequently affecting the availability and promotion of this food type. Encouraging policy changes and measures like subsidies for R &D in plant-based protein can help create a better environment for these alternatives (Springmann et al.,2018).

A coordinated effort by industry players, policymakers and positive consumer perception can together promote high sensory quality and cost -competitive plant proteins. (Springmann et al.,2018).

**Future Outlook and Recommendations**

**Global Implications**

As different societies across the world are transitioning towards plant -based protein, we have an opportunity to cultivate a healthier population that is aware of sustainable solutions addressing climate change, food security and human health. Traditional livestock farming has been the major contributor to greenhouse gas emissions, deforestation and biodiversity loss. Focussed changes to this pattern can help solve these issues reducing emissions and conserving land and water (Springmann et al.,2018). Plant-based proteins offer an efficient way to contribute to food security as it needs less inputs to produce providing important nutrients to the world population. Plant -based protein has a higher protein yield per hectare relative to livestock farming, fulfilling the need of an ever-growing population (Piercy etal.,2022). In addition to this, chronic ailments of heart and risks related to obesity can be lowered by effectively incorporating the need for plant- based proteins into the gene pool of the global food system (Eilam et al.,2023).

**Innovations on the Horizon**

Lab-grown and Algae-based proteins are becoming the new contributors to sustainable and affordable protein sources. Algae, especially microalgae is a rich source of essential amino acids, vitamins and bioactive compounds, and is therefore a highly nutritious and sustainable protein source. Algae production does not need an arable land. It can be cultivated internally with low water and nutrient input, providing an effective solution for areas with agricultural restrictions (Eilam et al.,2023). Recent progress in biotechnology has helped in the production of lab-grown or cultured meats that are very close to the sensory and nutritional characteristics of traditional meat, decreasing the environmental burdens. Using cellular agriculture, scientists have cultivated meat from animal cells in bioreactors, bypassing livestock farming and its adverse environmental effects (Alam et al.,2024). Also, the inclusion of microalgae into cultured meat systems might improve the sustainability of lab-grown proteins, adding to the nutrient -density of the growth substrate, increasing efficiency and reducing cost (Todhunter et al.,2024).

**Research and Development Recommendations**

Focused research and development initiatives are required to drive progress of the plant -based protein industry. One is to improve the sensory properties of plant-based proteins as the taste, texture and odour are important for consumer acceptance. Alternative processing strategies such as high-moisture extrusion, enzymatic hydrolysis and fermentation are being investigated to improve the functional properties of plant-based proteins and develop meaty textures (Piercy et al., 2022). Furthermore, contributing to more sustainable sources of protein by introducing under-used crops, such as pulses and duckweed, would also offer consumers a greater range of healthy food options (Eilam et al., 2023). R&D also focused on improving the bioavailability of plant-based proteins by tackling digestibility and amino acid completeness issues. Plant based substitutes can be more friendly to diets of all societies through fortification with micronutrients and amino acid balancing techniques (Todhunter et al., 2024).

**Policy Recommendations**

Plant-based proteins need to be incentivized and government policy in a great sorter of the three mentioned above. Implementing subsidies and financial incentives aimed at plant-based protein R&D and production is one of the most potent policy removes. Redirecting agricultural subsidies away from livestock farming and into sustainable protein alternatives ensures that governments build a more equal and resilient food system (Springmann et al., 2018). Policy support for plant-based food processing facility, as a step to develop a new market and allow increased accessibility, will also compound that effect. Likewise, public procurement policies have a major place in normalising plant-based consumption. The introduction of more plant-based alternatives in the meal programs of institutions including 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 provide transparency around labelling and nutritional claims to avoid misleading marketing tactics and to enable consumers to make informed choices around plant-based products (Alam et al., 2024).

**Market Expansion Strategies**

Plant-based proteins need to extend their market reach through consumer education and collaboration with other industries. For example, one approach could be the use of public health campaigns that emphasize the health and environmental benefits of plant-based diets. Clear and science-based messaging can shift scepticism leading more consumers to adopt plant-based eating (Eilam et al., 2023). Furthermore, partnerships between plant-based food producers and traditional food industry players can improve education on the benefits of these foods, contribute to product development, enhance distribution channels, and make plant-based foods more affordable. For instance, larger fast-food chains and grocery stores have started including plant-based options on their menus and in their product lines, which can contribute to the normalization of plant-based consumption among mainstream populations (Todhunter et al., 2024). Indeed, through food technology approaches, including 3D food printing and precision fermentation, new ways to produce high-quality plant-based foods at scale while still maintaining nutritional qualities and taste have emerged (Alam et al., 2024).

**Table 3: Emerging Plant-Based Protein Sources and Their Benefits**

|  |  |  |  |
| --- | --- | --- | --- |
| **Protein Source** | **Description** | **Benefits** | **Reference** |
| **Microalgae** | Single-celled organisms rich in protein and bioactive compounds. | Sustainable cultivation, high protein yield, and rich in essential nutrients. | Eilam et al. (2023) |
| **Lab-Grown Meat** | Meat produced through cellular agriculture techniques. | Mimics traditional meat while reducing environmental impact. | Alam et al. (2024) |
| **Duckweed** | High-protein aquatic plant used in food production. | Rapid growth, efficient nutrient absorption, and high digestibility. | Piercy et al. (2022) |
| **Pulses (Lentils, Chickpeas, etc.)** | Leguminous crops that are naturally high in protein. | Affordable, widely available, and rich in dietary fiber. | Springmann et al. (2018) |
| **Fermented Plant Proteins** | Proteins enhanced through microbial fermentation. | Improved digestibility, enhanced flavour, and increased bioavailability. | Todhunter et al. (2024) |

**Different Case Studies and Success Stories**

Innovations in food technology, consumer demand for sustainable alternatives and government policies have helped nationwide adoption of plant-based proteins become a reality. Around the world and within our regions there are examples where plant-based proteins are helping to solve environmental, economic, health and other problems.

Product such as Beyond Meat and Impossible Foods have transformed the plant-based food market by producing foods that resemble then however closely the cooking performance of traditional meat. These companies have employed complex processing methods including, but not limited to, high-moisture extrusion and heme protein fermentation, to make plant-derived alternatives more palatable. Plant-based meat substitutes in their production have lower greenhouse gas emissions than livestock farming (Kyriakopoulou et al., 2024) and they have lower water usage than traditional meat (Crowley et al., 2022). Furthermore, large-scale adoption of these alternatives can help to rein in intensive animal agriculture, curtailing deforestation and biodiversity loss whilst creating a sustainable means of meeting global protein demand (Springmann et al., 2018).

Countries like these have taken the lead in advocating for plant-based diets through policy and agricultural innovation. In fact, the Netherlands has made significant investments in alternative protein research, establishing itself as a leader in sustainable food production. Projects to increase the nutritional quality of plant-based proteins and to improve acceptability using targeted information campaigns have been funded by the Dutch government (Rojas Conzuelo et al., 2022). In a parallel manner, Canada has invested heavily in pulse-based protein sectors, acknowledging both the environmental and economic value of expanding plant-based food markets. Research into innovative plant proteins with enhanced functional properties and market viability has been propelled by the Canadian government Protein Industries Supercluster Initiative (Kumar et al., 2021).

Different community-based initiatives show the potential power of plant-based diets on health and environmental sustainability at local level. For example, Los Angeles and Berlin have executed public initiatives to promote plant-based eating, including meat -free school meal programs and plant-based restaurant subsidies (kyriakopoulou et al.,2024). They are designed to enhance the flavours of plant-based dishes and to promote healthier eating habits. Research has indicated that shifting school meals program towards plant- based foods can largely reduce students carbon footprints without compromising with national adequacy (Springmann et al.,2018). Moreover, plant-based diets can reduce cardiovascular diseases and obesity (Rojas Conzuelo et al.,2022) therefore it is even more necessary to implement the policy of opting these dietary patterns.

To sum it up, various studies and research mention about the potential benefits of plant-based proteins for the environment, including health and food security. Research, policies, market and product innovations play an important role in expanding plant-based food systems as well as supporting their sustainability in longer -term.

**Conclusion**

This shifting to sustainable protein sources will be fundamental in solving environmental, health and food security challenges of our time. Promising solutions from plant-based, microbial and alternative proteins hold the potential for lower-carbon and lower-resource consumption. Rapid advances in protein extraction, processing and formulation technologies have made them much more attractive than in the past as functional substitutes of conventional animal proteins. While advancements have been made, hurdles remain in terms of taste, cost and person perception that need to be overcome for widespread adoption. Incentives, consumer education and research policies will be instrumental in determining the future of sustainable food systems. Dietary diversification, with more plant and novel protein-based sources, can meet the needs for global nutrition while minimizing environmental consequences.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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