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# Alternative Proteins, Meat and Dairy Analogues: Are They Viable Consumer Options?

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**Abstract**

The increasing production and consumption of meat globally have raised serious concerns about environmental pollution, land and water requirements, greenhouse gas emissions, biodiversity loss and human health. Ensuring adequate protein requirement is one of the biggest challenges to food security. Therefore, new-generation meat and dairy analogues from a wide range of novel protein sources, such as upcycled plant materials, cultured cells, fermentation processes, fungi, algae and edible insects, have gained significant interest from both researchers and consumers. This study aims to review alternative proteins, meat and dairy analogues, and assesses their potential for an affordable, health-conscious, environmentally responsible and sustainable food future for humanity. The findings reveal that for the fourth industrial revolution in food production to successfully drive a protein transition, consumers must be engaged from the outset — including in the marketing of new products — to prevent rejection and resistance to dietary change. Clear and compelling communication is also needed to explain why and how novel meat and dairy alternatives surpass direct plant-based options, which have long offered significant benefits and remain a reliable and satisfying food choice.

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## Background

Food production accounts for over 26% of global greenhouse gas (GHG) emissions (Ritchie, 2019). Of these, approximately 60% are from animal products. In comparison, alternative proteins have a much lower environmental impact per kg of food (UNEP, 2023). A life-cycle analysis shows that animal-free products use 91% less land, 98% less water and 65% less energy while emitting 84% less GHGs than conventional animal products (Shabir et al., 2023). Animal product analogues (or alternatives) are the food products which are designed to mimic the taste, texture, appearance, and nutritional profiles of meat and dairy products without using living animals (Munialo et al., 2025). They have seen remarkable growth in recent years. The global alternative protein market size was valued at 11.88 billion dollars in 2025 and is projected to grow from 12.77 billion dollars in 2026 to 23.25 billion dollars by 2034. Alternative proteins include plant-based, microbial and fermentation-derived, cell-cultured, and insect protein, developed as substitutes for conventional animal protein sources (Fortune Business Insights, 2026). The global meat and dairy analogues market is a rapidly evolving sector, driven by consumer demand for sustainable, plant-based diets. In 2025, the global retail sales for these products have grown to approximately 28.9 billion dollars, with dairy alternatives heavily dominating the market (~78%) and plant-based meat continuing to expand despite economic price fluctuations (GFI, 2026). Recent developments have attracted substantial investments in financial and human capital, accelerating innovation and expanding market reach in this area (Broad et al., 2022). Research shows that when selecting these products, consumers prioritize taste and familiarity, especially when they complement traditional meat and dairy products. Environmental benefits associated with these alternatives are also essential factors and key drivers in the purchasing decision process, appealing to specific consumer segments (Parry & Szejda, 2019; Szenderák et al., 2022; Wali et al., 2024).

**Research Question**

The production of alternative proteins, meat and dairy products has been in the spotlight and has faced increasing scrutiny over the past few decades due to concerns about sustainability, environmental impact and excessive consumption (Delgado-Pando et al., 2023). Health and safety crises, most notably Bovine Spongiform Encephalopathy (BSE, or Mad Cow Disease) and avian flu, have further heightened public concerns about livestock products. In the 2000s, the United Nations Food and Agriculture Organization's (FAO) influential publication "*Livestock's Long Shadow*" created widespread awareness about the livestock sector's environmental toll (Farkas et al., 2023). Processing firms have been producing and marketing increasingly sophisticated animal product analogues, with consumer interest surging amid growing awareness of animal welfare, health concerns, and environmental sustainability (Smetana et al., 2023). The non-animal-sourced analogues are crafted to mimic the texture and qualities of traditional meat and dairy products, including milk, cheese, yoghurt, ice cream, and butter. Although milk and dairy products continue to be perceived favorably for their high levels of bioavailable essential nutrients, their per capita consumption has been steadily declining in Europe and the United States. In Europe, the average annual consumption per person dropped from 56.3 kg in 2011 to 53.4 kg in 2022 and is projected to decrease by an additional 394 mL by 2031 (Moore et al., 2023). Similarly, in the United States, dairy consumption has decreased by an average of 820 mL per year since 1975 (Moore et al., 2023).

In contrast, for instance, plant-based milk analogues have gained significant attention as consumers increasingly shift towards more sustainable eating habits. These alternatives made from soy and other legumes are generally fortified with essential vitamins and minerals, providing nutrition comparable to dairy milk, and yielding significant environmental benefits such as lower GHG emissions (by 59–71% per 250 mL serving), and less land and water use relative to traditional dairy milk production (Craig et al., 2023; Vatanparast, 2025). The global market for plant-based milk analogues is forecasted to reach 40.6 billion dollars by 2026 (Biscotti et al., 2023). Although dairy milk sales in the United States were 24.9 billion dollars, compared to 2.2 billion dollars for plant-based milk analogues, they follow different patterns. Between 2017 and 2019, annual dairy milk sales decreased by 456 million dollars, while milk analogue sales increased by 123 million dollars per year (Ramsing et al., 2023). By 2032, the global annual growth rate for non-animal dairy alternatives is estimated to rise by 9% (Moshtaghian et al., 2024).

**Approach and Expected Outcome**

This study examines the role of alternative proteins — including meat and dairy analogues — and evaluates their potential and viability in delivering an affordable, health-conscious, and environmentally sustainable food future. Through a comprehensive literature review, the study seeks to determine how effectively a protein transition can be achieved, and to explain why and how meat and dairy analogues may outperform direct plant-based options — foods that have long provided significant benefits and continue to serve as a reliable and satisfying dietary choice. It further explores how consumer engagement, particularly in the marketing of new products, can be leveraged to overcome rejection and resistance to dietary change.

**Protein Transition: Shifting Away From Animal-Sourced Products**

The protein demand for the existing 8.3 billion inhabitants in the world is about 290 million tonnes per annum. By 2050, a projected population increase of 2.3 billion people, largely from developing nations, will significantly intensify the global demand for protein. Currently, ~50% of the protein supplied globally is met by plant sources (Mehdizadehtapeh et al., 2025).

Meeting protein requirements is one of the biggest challenges for food security (van der Weele et al., 2019). With industrialization and the use of chemical fertilizers, the food supply, particularly in wealthy countries, has outpaced population growth, offering a wide range of dietary options. This has led to a protein transition, in which livestock-based foods now provide a large share of dietary protein, while plant-based foods have a declining presence in many diets (Drewnowski & Poulain, 2019). Relying on animal-sourced foods, however, comes at a higher cost to the natural environment, with red meat having the largest environmental footprint among all dietary options (Poore & Nemecek, 2018).

The era ahead in nutrition must be characterized by sustainability, regeneration, resilience, and improved human health. A dietary transition to more plant-based foods provides co-benefits in these areas. It is urgently necessary to respond to climate change, biodiversity loss, and the land, water, and air pollution associated with livestock-based foods (Marinova & Bogueva, 2022). Livestock has been shown to emit ~14.5% of the total anthropogenic greenhouse gas GHG emissions and is responsible for ~30% of biodiversity loss (Cheng et al., 2022). According to Aiking & de Boer (2020), a transition from primarily animal to plant protein-based products, including analogues and whole foods, combined with a reduction in overconsumption, losses and waste along the supply chain and at the household level, will result in better dietary behavior overall. Consumers can accelerate the transition to alternative proteins and contribute to a more sustainable protein sector. Alternative proteins can reduce the impact of our food system on the planet while providing healthier choices. This, however, needs to happen in an environment where consumers have reliable, trustworthy information about the various new food products already on the market.

**Emerging Alternative Proteins Sector**

The potential of the alternative proteins industry is luring many venture capitalists and other investors to continuously support the development of these new foods. According to the Good Food Institute (GFI), UK policymakers are advised, as part of the National Food Strategy, to urgently establish the country as a global leader in sustainable protein (GFI, 2024a). The shifting landscape of protein production in Australia also foresees growth, with a 3.1 billion-dollar opportunity in alternative protein categories by 2030 (Admassu et al., 2020). However, despite increasing consumer interest in plant-based alternative proteins driven by concerns about environmental and animal welfare (He et al., 2020) as well as health reasons, not all alternatives perform equally well (Sandich, 2023). This trend is fueled by the growing number of conscious consumers willing to adopt a non-meat, flexitarian or conscious lifestyle that does not exploit animals (Deloitte, 2023). A survey shows that 87% of consumers in the US, UK, Netherlands, and Germany fall into these categories (Deloitte, 2023). The main driver for these changes is the lower environmental impact of alternative proteins compared to animal-based foods. According to Markets and Markets, the highest growth in alternative proteins is anticipated in the Asia Pacific region, with a compound annual growth rate (CAGR) of 14.3% (Markets and Markets, 2024). Predictions for growth are also estimated by the UK Royal Society, where the alternative meat industry's size was worth 1% of the global meat industry in 2019 (around 14 billion dollars) and could grow to 10% (over 140 billion dollars) within ten years (The UK Royal Society, 2019). Another estimate by RethinkX projects that alternative novel proteins will account for 75% of the current animal-based protein market by 2030 (RethinkX, 2021). Amongst alternative proteins, plant-based proteins are currently the fastest-growing food trend but depend on soy and peas. Exploiting opportunities to extract upcycled plant and seaweed proteins is encouraged by legal authorities, such as EU-granted projects, to address annual global food loss and waste (FLW). For instance, the IPSUS project (https://ipsus.org/en/) is supported by the Horizon 2020 joint FOSC and SUSFOODS2 program, national agencies of the partner countries, including UK, Italy, Romania, Morocco, France, and Türkiye, from 2022 to 2025, to deliver upcycled plant and seaweed protein-based meat and dairy-free cheese analogues (IPSUS, 2024). With the list of alternative proteins long and evolving, looking more specifically at their origins, the technologies used, and the challenges they pose are of interest.

**Animal Product Analogues**

This section explores the leading categories of animal product analogues — from plant-based meat and dairy formulations to cultured meat, precision fermentation, mycoproteins, algae, and edible insects — outlining their respective advantages and key considerations.

Plant-based Meat And Dairy Analogues

The plant-based meat and dairy analogues are formulated to replicate the sensory and nutritional profiles of animal products (Nájera Espinosa et al., 2026). They offer some advantages in sustainability and fat profiles, but require consideration regarding nutrient density, processing levels, amino acid completeness, cost, and consumer adoption (Malek & Umberger, 2023).

The plant-based meat analogues (PBMA) are designed to serve as alternatives to traditional meat in the human diet. Meat analogues such as tofu have existed since at least 200 BCE (Tan, 2008). In the US, John Harvey Kellogg pioneered the development of meat replacements made from nuts, grains, and soy, commencing around 1877, to nourish patients at a health resort (Shurtleff & Aoyagi, 2004). The PBMAs are also familiar to the European markets, where they have existed for decades. Despite their ancient origins, tofu and tempeh became available in the West only in the 1960s, influenced by oriental flavors in food culture during the hippie movement (Rödl, 2019; Sui et al., 2024). Nevertheless, during the 1990s, only a few firms offered first-generation PBMAs, which were narrowly based on available processes and texturized plant protein (TPP) (He et al., 2020). Around the 2010s, companies such as Impossible Foods and Beyond Meat popularized ready-made PBMAs for ground beef and chicken nuggets. In the last decade, new-generation meat analogues derived from a wide range of novel plant sources have attracted the attention of researchers and consumers (Lee et al., 2020; Frezal et al., 2022).

The PBMA market is poised for significant growth, expected to rise from 1.89 billion dollars in 2021 to 4.04 billion dollars by 2027, and to ~85 billion dollars by 2030, with a CAGR of 13.5% (GWR, 2023; Markets and Markets, 2024). According to the GFI's analysis, 2,000 commercial-scale extrusion lines will be required if the PBMA market reaches 6% of the total meat production volume, 25 million tonnes annually, by 2030 (GFI, 2024b). The urgency is justified by the better environmental performance of the PBMAs, whose production emits up to 90% less greenhouse gas emissions and uses up to 99% less land than farming animals (GFI, 2024a).

The PBMA are generally composed of water (50–80%), texturized plant protein (15–20%), non-texturized protein (10–25%), flavorings (3–10%), fat (0–15%), binding agents (1–5%), colorants (0–0.5%) and other specific ingredients to improve the final product appeal (Lima et al., 2022). Research on alternative proteins and meat analogues has focused on functionality, processing, industrial applications, and the valorization of by-products (Banach et al., 2023). Most food processing techniques can be classified into dehydration, baking, canning, and extrusion. Major critical problems in food processing include the nonlinearity of the process, the complexity of biomaterials, and the extensive range of parameters (Nayak et al., 2020). Specifically, PBMA is generally manufactured by thermo-mechanical processing, also called "extrusion technology" with low-moisture (20–40%) or high-moisture (40–80%). Other technologies used are shear cell technology, self-assembly, wet- or electro-spinning, freeze-casting and culturing mycoproteins. However, the global industrial production mainly relies on extrusion technology (Sun et al., 2021). Extrusion is a cooking process that uses high temperatures (>100 °C) and pressures for a short time at standard conditions. Time and temperature are critical control points (Bogueva & McClements, 2023). Raw materials undergo physico-chemical transformations during extrusion due to high shear, heat, and pressure (Morantes et al., 2020). In the extrusion process, low-moisture extrusion (LME) ($a_w$ < 30%) has limited acceptance due to poor mouthfeel. It also requires high energy (1000 kJ/kg) and rehydration before use. On the other hand, high-moisture extrusion (HME) ($a_w$ > 40%) has some advantages, such as lower energy input, no waste discharge, higher efficiency, and texturized quality. However, it also has several drawbacks in texture and juiciness. Thus, HME is more suitable for developing PBMA (Schmid et al., 2022; Andreani et al., 2023). Nonetheless, due to a lack of in-depth mechanistic understanding of the extrusion process for plant proteins, it is considered a "*black box*" with limited insight into what happens inside, posing significant obstacles to design-led manufacturing and the scale-up of PBMA (Ahmad et al., 2022). The HME process is also a complicated multi-input/output system because feed constituents (mainly protein) leave the system as a transformed product (Faisal, 2022). While PBMAs can replicate meat, especially the appearance, sensory and nutritional considerations persist. They are often classified as highly processed and potentially sacrificing nutritional value by excluding some essential ingredients (Rubio et al., 2020). It should also be acknowledged that additives are essential for highly processed products, and such items may incur higher environmental impacts. Accurate assessment of the nutritional content of PBMAs is crucial, particularly the bio-accessibility and bioavailability of nutrients, as well as the safety risks associated with their consumption (Bogueva & McClements, 2023).

The plant-based dairy (milk) analogues, known as such since approximately 1200 AD, have a rich global history. Coconut milk, with its roots in India and Southeast Asia, has the longest tradition. Used both as a beverage and a nutritional and ceremonial ingredient, it has a deep cultural significance (McHugh, 2018). Soy milk is traced back to its discovery in China in 1365, when it first found its place in Chinese cuisine. Its evolution includes transitioning to being consumed as a beverage around 1866 (Shurtleff & Aoyagi, 2013). The first soymilk factory near Paris was established in 1910, coinciding with the grant of the first soymilk patent titled "Plant-based milk and its derivatives" given to the Chinese citizen, biologist and engineer Li-Yu-Ying. The 1970s and 1980s witnessed a surge in global popularity for soy milk (Shurtleff & Aoyagi, 2013). Almond milk is thought to have originated in the 13th century, making its mark in history and establishing itself as an early plant-based milk alternative. It can be traced back to references in Baghdadi and Egyptian cookbooks, as well as to early mentions in English literature. In 1390, almond milk was documented for the first time in England, and its widespread adoption in Europe occurred during Lent, marking the emergence of the first popular non-dairy milk analogue in the Western world (British Food History, 2019). Its historical presence across diverse culinary traditions underscores its longstanding use as a versatile and plant-based beverage. A variety of other plant-based milk analogues, based on nuts (e.g., macadamia), legumes (e.g., peas), and grains (e.g., oats), became popular in recent years (Shurtleff & Aoyagi, 2013).

Plant-based milk analogues are on the rise among consumers, driven by environmental concerns but also by medical reasons such as lactose intolerance and allergies to cow's milk protein. The plant-based milk analogues initially relied predominantly on soy and almond. Now, they encompass various solutions crafted from rice, oats, nuts, and legumes, showcasing an expanded, more inclusive array of options (Jeske et al., 2018). The global alternative dairy market is expected to grow from 29.18 billion dollars in 2023 to 66.91 billion dollars in 2030 with 12.6% CAGR (GWR, 2024).

People pursuing a healthier lifestyle and those concerned with animal welfare, including vegetarians and vegans, contribute to the increasing popularity of plant-based milk analogues. In Australia, individuals presently consume around half a metric cup of milk analogues weekly (or 17 g per person-day), with soy and almond milk consumption rising among other types of milk analogues (ABS, 2022). In certain countries, alternative products, including plant-based dairy analogues, have faced scrutiny. Notably, in Türkiye, the Ministry of Agriculture and Forestry has prohibited the production and sale of vegan dairy (cheese) alternatives that closely resemble traditional dairy cheese (Southey, 2022). Furthermore, the existing legislation in Türkiye explicitly states that the term "cheese" cannot be employed to describe dairy-free analogues to avoid potential consumer confusion. This regulation was underscored in the latest update to the Turkish Codex Food Regulation. Some argue that an action like this violates the rights of consumers and manufacturers of plant-based analogues (Axworthy, 2022).

Plant-based milk analogue processing can be done with any nuts and other plants. Uncertainty exists, and there is a need for greater certainty regarding the nutritional parity between plant-based milk and its dairy counterparts (Drewnowski et al., 2021). Soy milk, for instance, closely matches the nutritional profile of cow's milk while being cholesterol-free and gluten- and lactose-free (Hossen et al., 2022). It also provides more proteins and is enriched with other nutrients, such as vitamins $B_1$ and $B_6$, folic acid ($B_9$), vitamins E, $D_2$ and $K_1$, magnesium (Mg), manganese (Mn), iron (Fe) and copper (Cu), compared to dairy and other plant-based milk analogues (Walther et al., 2022). Beyond their growing appeal, nut milks offer advantages such as lower land requirements, carbon sequestration by trees during growth, and the production of valuable woody biomass at the end of their life cycle (Marinova & Bogueva, 2020). Plant-based milk analogues frequently exhibit lower protein content and rely on varied levels of fortification for calcium and vitamins A and D. Issues with added sugar and saturated fat can be of concern. Establishing nutrient standards for analogues is imperative, requiring collaboration among the food industry, public health regulatory authorities, and standardization bodies such as the Codex Alimentarius (Drewnowski et al., 2021).

### Cultured Meat

As an emerging and technically intricate component of the modern food supply, cultured meat is developed using cellular agriculture methods that were first established within regenerative medicine. It has the potential to significantly reduce GHG emissions, pollution associated with large-scale industrial agriculture, deforestation (Xie et al., 2025), the risk of foodborne illnesses (e.g., *Escherichia coli* or *Salmonella*), avoids the routine use of antibiotics and requires significantly less land and water than traditional livestock farming (Zandonadi et al., 2025). However, regulatory approval is inconsistent worldwide; it is commercially approved in several markets including Singapore, the USA, and Israel (Choi et al., 2025). Moreover, consumer acceptance varies; barriers include psychological hesitation toward "lab-grown" food, concerns about the use of fetal bovine serum (FBS) in older research methods, and religious dietary compliance (Gil et al., 2026).

Meat produced by culturing animal cells *in vitro* conditions is known as cultured, cultivated or lab-grown meat. This innovative approach involves taking a small sample of animal cells, usually muscle cells, and placing them in a controlled *in vitro* environment, allowing them to multiply and develop into muscle tissue. The process aims to create a product that closely resembles traditional meat without the need to raise and slaughter animals (Lee et al., 2024). Cultured meat is a nascent technology among other alternative protein sources which has undergone notable developments since its initiation. The technology represents a pioneering approach to meat production, based on the extraction of multiple stem cells from a living animal. A distinctive feature of this process is the avoidance of animal slaughter. Stemming from the amalgamation of stem cell isolation, cell culturing and tissue engineering techniques (Post, 2012), cultured meat production entails the growth of individual muscle fibers outside the traditional livestock setting. Noteworthy progress was marked by the introduction of the first cultured meat beef burger in August 2013, when the development was still in its incipient stages (Post, 2014). The fundamental concept centers on fostering the growth and development of harvested cells into cultured meat, thereby offering a promising avenue for sustainable, humane protein production. Subsequent advancements have expanded the scope of cultured meat production to encompass diverse sources, including fish (Xu et al., 2023) and chicken, and have led to regulatory approval for market entry in Singapore (Marsh, 2023; Trager, 2020) and the United States (Aleccia & Ungar, 2023). Exotic, endangered or extinct animals (e.g. the Australian Start-up Vow, which produced mammoth cultured meat) are also interesting. A significant advancement in the methodology is substituting fetal bovine serum (FBS) with a plant-based growth medium – animal-component-free special liquids that supply essential nutrients to cells, promoting their growth and proliferation (Mosa Meat, 2020). Furthermore, economic considerations have come into play, with significant reductions in production costs (Lucas, 2019) driven by substantial financial investments (Choudhury et al., 2020).

Predictions foresee cultured meat, capturing 10% of the market by 2030 and possibly reaching 35% by 2040 (Lymbery, 2023). The future of cultured meat relies on continued interest and support from various stakeholders, encompassing investors, Silicon Valley entities, animal welfare organizations, and the traditional meat industry (van der Weele et al., 2019). Collaborative support is essential to address significant technological and regulatory challenges for the ongoing progress of cultured meat. Obstacles related to technology limitations, consumer acceptance and legal considerations persist (Ching et al., 2022). The intersection of scientific innovation, economic factors and regulatory approvals highlights the dynamic landscape of cultured meat as an emerging contender in the pursuit of sustainable and ethical protein sources.

Precision Fermentation

Precision fermentation is a biotechnological process where genetically engineered microorganisms—like yeast or bacteria—are programmed to act as micro-factories. By consuming simple nutrients, these microbes synthesize specific, highly pure compounds (such as proteins, fats, or vitamins) used as sustainable alternatives to animal-derived ingredients (Hilgendorf et al., 2024). This technology requires significantly less land and water than conventional livestock farming while generating fewer GHG emissions, but high capital energy costs and scale-up complexities remain the primary hurdles for commercial viability (Adeyeye et al., 2026).

Since Neolithic times, fermentation has produced a wide range of foods and beverages. The fermentation method, primarily used to extend the shelf life of foods and preserve them, also plays a significant role in making plant-based alternatives to meat and dairy products (Owusu-Kwarteng et al., 2022). The term "precision fermentation" refers to fermentation processes that emerged in the fourth industrial revolution of the food industry, which aims to improve the quality and safety of products, reduce loss and waste, improve production efficiency and significantly diminish its environmental footprint by using transforming and revolutionizing technologies (Hassoun et al., 2023). Precision fermentation uses microbial hosts to produce high-value functional food ingredients, such as lipids, carbohydrates, flavors, enzymes, vitamins, colorants and antioxidants. Its main justification is sustainability, an attractive option for transforming food systems (Chai et al., 2022). Through precision fermentation, proteins are mixed with sugar, minerals, water and plant-based fats to create animal-free dairy products such as milk and ice cream (Teng et al., 2021).

While the global market for PBMA and plant-based dairy alternatives (PBDA) manufactured using fermentation was valued at 329.29 million dollars in 2021, this figure is expected to reach 422.26 million dollars by 2026. Moreover, fermentation's PBDA and PBMA account for 26.30% and 8.56% of the total fermented plant-based food analogues sold in the market (Boukid et al., 2023). Koch et al. (2021), in their studies on the future of the dairy industry, note the potential for dairy analogues produced via precision fermentation to replace traditional dairy products. However, in another study measuring consumer perceptions, 40% of consumers directly rejected animal-free dairy products. The reasons for this objection were the possible presence of chemicals in these foods, their unnaturalness, and the long-term uncertainty about their impact on human health after consumption (Broad et al., 2022).

Precision fermentation continues to face multiple challenges. One is the high production costs, as precision fermentation technologies are currently expensive, leading to higher product prices than conventional alternatives. This hinders widespread adoption, especially in terms of consumer affordability. Another issue concerns the regulatory and safety environment. If genetic engineering and genetically modified organisms (GMO) are involved, precision fermentation requires rigorous testing to ensure the safety of its products. Regulatory considerations pose challenges for addressing potential risks to human health and the natural environment (Knychala et al., 2024). Ongoing studies and emerging trends center on the following key areas: (1) artificial intelligence and machine learning for strain optimization and bioreactor control (Priyadharshini et al., 2025), (2) next-generation microbial hosts for the optimization of eukaryotic hosts (Singh & Kumar, 2025), (3) alternative feedstocks & upcycling for alternative and cheap substrates (Obayomi et al., 2026), (4) expanding ingredient portfolios (Zuo et al., 2024), and (5) advanced downstream processing to significantly reduce the cost of target molecules (Obayomi et al., 2026), respectively.

There are also ethical concerns, mainly related to the use of GMO in food production. Transparency and clear communication are essential to address consumer concerns about the ethical implications of consuming products derived from precision fermentation. Furthermore, precision fermentation may contribute to the concentration of power in large corporations, limiting market competition and potentially hindering diversity and innovation within the industry (Thomas et al., 2023).

## Mycoproteins

Mycoprotein is commonly used as a meat substitute due to its fibrous, muscle-like texture and savory "umami" flavor (Firincă et al., 2026). Producing mycoprotein is highly resource-efficient compared to conventional animal agriculture, its production process shares similarities with brewing, using industrial bioreactors, and it has Generally Recognized as Safe (GRAS) status from the US Food and Drug Administration (FDA) authority (Khalasi et al., 2026).

Mycoprotein, a protein-rich food, is produced from the filamentous fungus *Fusarium venenatum* (Saeed et al., 2023). It is consumed as an alternative to animal protein owing to its amino acid content and cost-effectiveness (Shahid et al., 2023. Since mycoproteins are considered an alternative to meat, they are used in fermented food to improve the nutritional value and prolong shelf life (Souza Filho et al., 2019). Although truffles and mushrooms are fungi, they are unsuitable meat analogues due to low protein content (Derbyshire & Delange, 2021). Mycoprotein was first discovered in the early 1960s. Its origins date back to concerns about worldwide protein shortages, when scientists sought to develop a microbial protein source. In the area of Marlow, Buckinghamshire, UK, *Fusarium venenatum* was first reported to synthesise mycoprotein (Saeed et al., 2023). Mycoprotein is now produced by fermentation in many countries under the brand name Quorn™ (Finnigan et al., 2019; Derbyshire, 2022).

The advantages of mycoprotein are that it is low in fat and sugar, high in fiber and protein, and contains no cholesterol or trans-fat. According to the European Commission (EC), nutritional content made for mycoprotein is high in protein (at least 20% of the energy value of the food), low in fat (< 3 g of fat per 100 g of solids), low in saturated fat (< 1.5 g of saturated fatty acids per 100 g of solids) and high in fiber (at least 6 g fiber per 100 g). Rates, however, may vary between countries; in the United States, for example, 20% refers to the highest of the Daily Value per reference amounts customarily consumed (RACC). According to the study by Derbyshire & Ayoob (2019), when mycoprotein (Quorn Minceis) is compared with beef (roasted, cooked), salmon and cheese (cheddar), the following are their protein contents: Mycoprotein – 12 g protein per 85 g, beef – 15 g protein per 85 g, salmon – 17 g per 85 g, cheese – 14 g per 55 g. Moreover, mycoprotein also provides zinc (Zn), which in the same study was shown to be 6.6 mg Zn per 85 g (Derbyshire & Ayoob, 2019).

Interest in mycoprotein consumption and its effects on human health and nutrition has increased, as demonstrated by numerous studies (Hashempour-Baltork et al., 2020). It has been compared to different meat types and mushrooms. Whilst there is evidence that uncontrolled meat consumption plays a role in the development of cardiovascular disease, mushrooms and plant-based products are essential for protecting heart health due to their high fiber content. It is now emphasized that mycoprotein-based products can have similar effects on the human body (Colosimo et al., 2020).

With the increasing food crisis, the issue of food accessibility has been raised, and adding mycoprotein to foods instead of meat, meat products and dairy products has been tested in studies (Zeng et al., 2023). In a study by Hashempour-Baltork et al. (2023), mycoprotein was used as a substitute for nugget meat, and it was found to have a similar texture and sensory properties to those of a chicken meat substitute in the nugget formulation. A different study comparing milk protein and mycoprotein bolus test drinks concluded that the bioavailability of amino acids was similar between the two (Dunlop et al., 2017). Overall, mycoprotein will have an important role as an alternative to meat and milk proteins.

## Algae

Serving as a food source for thousands of years, various cultures have cultivated algae (Diaz et al., 2023; Ullmann & Grimm, 2021). Algae drive environmental sustainability through their rapid growth, high-protein content, and unique photosynthetic efficiency. They directly advance climate action, food security, and pollution control by acting as renewable resources that require minimal arable land and freshwater compared to conventional agriculture (Das & Bhattarai, 2025). When narrowed down to food security, the challenges of algal commercialization shift from energy density to consumer safety, regulatory approval, and sensory traits (Rawindran et al., 2026).

Algae are divided into two main groups, namely: microalgae, representing single-celled photosynthetic microorganisms adaptable to both salt and freshwater, and macroalgae, consisting of multicellular aquatic plants categorized as green, red or brown, each with unique proteins, carbohydrates and fats suitable for diverse applications (Kirkby, 2023) and rich in antioxidant vitamins (Sansone & Brunet, 2020). They promise future food security, as algae requires minimal non-arable land and freshwater, yield abundantly, and enhance water quality by absorbing excess nutrients (Kirkby, 2023). With their high protein and nutritional content, microalgae could emerge as the future of sustainable superfoods in a rapidly changing world. Algae possess essential qualities as a sustainable food source, providing highly digestible proteins, lipids and carbohydrates while being rich in essential fatty acids, vitamins and minerals (Diaz et al., 2023). For instance, blue-green algae, among Earth's most primitive life forms, have been consumed by humans for centuries as food and used for medicinal purposes (Ku et al., 2013). Packed with bioactive compounds, including phycocyanin, carotenoids, gamma-linolenic acid, fibers, and plant sterols, blue-green algae promote optimal human health (Ku et al., 2013).

Algae, particularly microalgae, offer numerous health benefits. They contain components which promote cardiovascular health and have anticancer, anti-inflammatory, anticoagulant, antiviral, antibacterial and antifungal effects (Naik et al., 2024), including polyunsaturated fatty acids (PUFAs), sulfated polysaccharides, and antioxidants – such as carotenoids and phycocyanin, protein hydrolysates and individual peptides (Li et al., 2019; Magnabosco et al., 2025; Masoumi et al., 2025). This highlights their significant potential for applications in human health and medicine.

Integrating new technology and scaling up are already underway; algae production can have a significant impact (Ullmann & Grimm, 2021). While promising at the lab scale, further research on agricultural-scale production is crucial to compare costs with those of staple crops, a key barrier to large-scale adoption of algae for human food or animal feed (Koyande et al., 2019; Diaz et al., 2023). Researchers are working on new strains, improved production methods, and higher yields of microalgae, aiming to enhance efficiency and cost-effectiveness in the manufacturing of microalgae-based food components (Naik et al., 2024). Further exploration of the safety and nutritional value of different microalgal strains is key to facilitating commercialization and overcoming potential barriers to incorporating microalgae into food products.

Edible Insects

Edible insects (entomophagy) serve as a highly sustainable alternative to conventional livestock, providing dense nutrition with a fraction of the environmental footprint (Ke et al., 2025). Despite their high biological efficiency, edible insects face severe structural bottlenecks that prevent them from securing the global food supply chain, including high production costs, psychological barriers and consumer rejection, and safety and regulatory hurdles (Traynor et al., 2024; Haghayeghi et al., 2025).

Edible insects, preferred for their amino acid and fatty acid content, are traditionally consumed in many Southeast Asian countries, sub-Saharan Africa, Australia, and Latin America (Balinga et al., 2004; Lange & Nakamura, 2021a). The consumption of edible insects, often referred to as entomophagy, is not a new custom; it dates to the past and remains part of the human diet today (Lange & Nakamura, 2021b; Ojha et al., 2021). Insects are consumed in traditional culture using methods such as roasting, steaming, frying, smoking, curing and stewing to improve the foods' sensory properties and extend their shelf life (Ojha et al., 2021). Choosing insect species depends on their nutritional value, religious beliefs, availability/access, suitability and social traditions, but the most consumed species are *Lepidopterans, Orthopterans* and *Hymenopterans* (Tang et al., 2019; Meyer-Rochow et al., 2021). The market size of edible insects in 2018 was over 400 million dollars, and the insect industry aims to grow to over 1.4 billion dollars by 2025 (Demirci & Yetim, 2021).

Although the nutritional content of edible insects may vary depending on their habitat, they generally have high levels of fat, protein, fiber, vitamins, and minerals. They have amino acid profiles like those of animal foods, but with higher protein content. When examined by species, the average fat content of *Lepidoptera*, *Isoptera*, *Orthoptera*, *Blattodea* and *Coleoptera* is 27.6%, 32.7%, 13.4%, 29.9% and 33.4%, respectively (Rumpold & Schlüter, 2013). There are two main types of carbohydrates found in insects: chitin and glycogen, and their average carbohydrate content ranges from 6.71 to 15.98%. Moreover, insects are considered good sources of Cu, selenium (Se), Zn, Mn, calcium (Ca), and Fe. Research evidence shows that edible insect species, such as grasshoppers, locusts, and crickets, provide significant amounts of Mg (Imathiu, 2020).

Studies have recently partially used insect proteins to replace meat in meat products. In a study comparing mealworms and beef in terms of nutrition, beef had higher fat, protein, and metabolizable energy than mealworm larvae. Compared to mealworms, beef is higher in glutamic acid, lysine and methionine and lower in isoleucine, leucine, valine, tyrosine and alanine (Kröncke et al., 2023). Beef contains more palmitoleic, palmitic and stearic acids than mealworms, while the amount of essential linoleic acids is much higher in mealworms. Except for vitamin $B_{12}$, mealworms generally have a higher vitamin content than beef (Tekiner et al., 2022). In a separate study in which mealworm larvae (*T. molitor*) and silkworm pupae (*Bombyx mori*) were substituted for 10% of lean pork in emulsion sausages, protein and fat content were higher following insect substitution. No significant difference in moisture content was found. Mineral levels also increased with the addition of insect meal. However, the high fat content of insects needs to be considered in the formulation of the final product (Acosta-Estrada et al., 2021).

As interest in edible insects increases, food safety has also come to the fore. Given the limited knowledge of food safety in many countries, studies on this subject are critical. Potential food safety hazards are grouped into three categories: chemical, allergens, and

Table 1. The pros and cons of plant-based animal free products, cultured meat, precision fermentation, mycoproteins, algae, and edible insects

| No | Product | Pros | Cons | Reference(s) |
|---|---|---|---|---|
| 1 | Plant-based animal-free products | Mass-market availability; cholesterol-free; reduced land and water use; high fiber | Often ultra-processed; allergen concerns; flavor and texture frequently require masking ingredients | Lee et al. (2025) |
| 2 | Cultured meat | Identical to traditional meat; no animal slaughter; lower risks of foodborne pathogens and antibiotic use | Currently expensive; less scalability and facility-energy challenges; still relied on animal-derived serum in early culture phases | Orsini et al. (2026) |
| 3 | Precision fermentation | Identical taste, texture, and functionality to animal-based proteins; efficient resource use, cutting GHG emissions (by up to 97%) relative to traditional agriculture | Highly regulated genetic modification (GMO) processes; massive capital investments to scale infrastructure | Özpınar et al. (2026) |
| 4 | Mycoproteins | Complete protein profile; high in dietary fiber and low in saturated fats; scalable production | High RNA content-associated digestive issues; distinct earthy flavor profile for flavoring | Gnaim et al. (2025) |
| 5 | Algae | Fast growth rates; rich in essential fatty acids (Omega-3s), vitamins, and antioxidants; grown in wastewater or the ocean | "sea" or "fishy" flavor; processing to extract proteins cleanly | Onyeaka et al. (2022) |
| 6 | Edible insects | Resource-efficient; excellent sources of protein, healthy fats, and micronutrients such as zinc and iron | "Yuck factor" and cultural resistance in Western markets; high risk of certain allergens | Acosta-Estrada et al. (2021) |

biological (Murefu et al., 2019). As most edible insects are protein-rich, some insects and foods derived from them may be potential sources of allergens (Johansson et al., 2004; Imathiu, 2020). Edible insects pose risks, including the presence of harmful microorganisms, heavy metals, drug residues, allergenic factors, or parasitic creatures (EFSA, 2015). For example, the intestinal microbiota of insects accounts for 1-10% of their total body weight, and it cannot be removed before consumption (Tekiner et al., 2022). Although findings on the allergenic potential of edible insects are limited, research indicates that certain proteins, including arginine kinase, may be allergenic (López-Pedrouso et al., 2023). Apart from arginine kinase, other common allergens associated with edible insects include α-amylase and tropomyosin; The European Food Safety Authority (EFSA) (2015) highlighted that consumption of the evaluated insect proteins could potentially lead to allergic symptoms (Cunha et al., 2023). In summary, the pros and cons of plant-based animal free products, cultured meat, precision fermentation, mycoproteins, algae, and edible insects are tabulated in Table 1.

## Key Actors and Authorities in Alternative Protein, Meat and Dairy Analogues

The alternative protein ecosystem—encompassing plant-based meat and dairy analogues, cultured meat, precise fermentation-derived, mycoproteins, algae, and edible insects—is primarily governed and driven by regulatory authorities, industry innovators and markets, and consumers (Johnson et al., 2023). The regulatory authorities (government bodies) evaluate safety, mandate labeling requirements, and grant commercial market approvals (Marco et al., 2021).

### Regulatory Authorities

In the United States, the Food and Drug Administration (FDA) regulates plant-based and fermentation-derived proteins; co-shares oversight of cultivated meat cell collection and growth stages, and the Department of Agriculture (USDA) oversees the harvesting and labeling stages of cultivated meat; enforces strict guidelines on when analogues can use words like "meat," "milk," or "beef." (Charteris & le Coutre, 2025). The European Union (EU) EFSA enforces the strict Novel Food Regulation. It requires comprehensive toxicological testing, making the EU market the slowest and most difficult to enter for cultivated and precision-fermentation products (Carocho et al., 2017). The Singapore Food Agency (SFA) is the world’s pioneer regulator. It was the first globally to approve cultivated meat (2020) and microbial proteins, positioning Singapore as the primary global test market (Li et al., 2025). The other key regulatory authorities are the Australia/New Zealand (FSANZ) and Israel (Ministry of Health), and have also issued historic approvals for cultivated beef, dairy, and cell-based components (Senyange et al., 2024; Johnson & Monaco, 2025). These developments prove that cultivated beef, dairy, and molecularly identical components are successfully transitioning past the "novel concept" phase into highly regulated, standard commercial food categories across multiple continents.

Industry Innovators and Markets

Many analysts anticipate robust growth in the future global alternative protein market. Companies are exploring novel production methods and ingredients, such as spinning proteins into fibrous textures resembling animal muscle and employing innovations to reduce protein off-notes (Grylls, 2023). In recent years, not all meat analogue start-ups have achieved financial independence. Some were forced to close, including the United States-based plant-based meat companies Hooray Foods and Nowadays, Meatless Farms (Flood, 2023), the plant-based egg company Unreal Foods and the vegan bacon company Remastered Foods (de Sousa & Shanker, 2023). Other companies are engaged in mergers, such as the Australian All G Foods' plant-based division (Buds burger brand) and Fenn Foods (Veef brand), which united under the Aussie Plant Based Co company (Gloria, 2023). The stocks of some leading brands, Beyond Meat and Impossible Foods, have fallen significantly (Shanker, 2023; Forbes, 2023). Market analysts believe this does not diminish the industry's potential but reflects a shift in the funding landscape impacting brands (Grylls, 2023). It underscores the need for adaptability, emphasizing that meticulous planning alone is not enough to ensure success. The closures signal broader changes, prompting a reassessment of funding approaches and business models in the meat alternatives' start-up ecosystem. Analyzing these closures provides insights for the remaining companies to navigate the dynamic landscape effectively and foster resilience in the face of challenges.

The growth of the alternative proteins market is also heavily influenced by pricing. Price is a major hurdle to the widespread adoption of alternative proteins for mass consumption. Some major players in the alternative protein market are considering price increases to achieve parity with conventional meat products. Impossible Foods has implemented price reductions to enhance the accessibility of its products to the broader consumer base. The company slashed prices in 2021 for distributors and retailers, aiming to match its costs with those of traditional meat (Cattlin, 2022).

Regarding other alternative proteins, despite the considerable potential of algae for food and feed production, these products have yet to become widely recognized as mainstream commodity food options. There needs to be greater clarity between the potential of algae and their current market status (Mylan et al., 2023). Another major issue around growing seaweed, currently seen as a promising strategy for mitigating global warming and food sustainability, is climate change itself. It may be challenged in its cultivation due to increasing ocean acidity, which is unfavorable for healthy seaweed growth. Additionally, at a larger scale, seaweed farms may become invasive and obstruct light, potentially threatening ecosystems (Khan et al., 2024).

Consumers

In the alternative protein ecosystem, markets and consumers represent two entirely different dimensions of the commercial value chain. While markets refer to the economic infrastructure and channels where products are traded, consumers are the individuals who make the final decision to purchase and eat those products. The primary difference is that market actors focus on structural feasibility and profitability, whereas consumers focus on personal experiences, sensory traits, and social factors (Srinivasan et al., 2024; Civero et al., 2025).

Overcoming consumer preferences also presents a challenge, necessitating robust promotion to encourage behavior change. Consumers are currently navigating the diverse options in the alternative proteins market, with some showing a mix of curiosity and varying sentiments. Despite the recent surge in interest, alternative proteins have yet to gain widespread consumer acceptance (Onwezen et al., 2020), especially among younger consumers (Bogueva & Marinova, 2020). The overall appearance and taste pose significant barriers for consumers, particularly those yet to experience alternative proteins. This is particularly evident for insects (Sogari et al., 2019) and cultured meat. It was found that 52% of Australian adults have not yet purchased alternative meat or protein products (ABS, 2022; Malek & Umberger, 2023). They may consciously reduce or limit their meat consumption, becoming flexitarians and choosing other, more sustainable food options. Even among consumers who already incorporate alternative proteins into their diet, they desire 'better-tasting products' within the plant-based category.

Similarly, consumers perceive lab-grown meat negatively across various attributes, except for its association with animal friendliness. Interestingly, beliefs about environmental friendliness do not affect individuals' willingness to consume lab-grown meat (de Oliveira Padilha et al., 2022). The primary determinants of food choices include 'taste,' 'health/nutrition,' and 'price' (Malek & Umberger, 2023). Acceptance of lab-grown meat among consumers might be achievable through marketing efforts that address current barriers, such as negative perceptions of attributes like palatability, healthiness, and safety, and that highlight more positive motives for consumption (Verbeke et al., 2021).

**Food Safety Aspects**

According to the Nova Food Classification System, PBMA are ultra-processed products with complicated formulations. Microbiologically, the background microorganisms in high-moisture extruded PMBA may differ from those in animal-origin meat products due to their higher moisture content. For instance, spoilage bacteria and pathogens may easily adhere, invade, and proliferate due to their nutritional environment, pH, and internal structure. Some endospore-forming bacteria like *Clostridium* spp. or *Bacillus* spp. may also survive the heating regime (Hadi

& Brightwell, 2021), as previously detected in a PBMA facility in 2022 (Liu et al., 2023), as well as *Lactilactobacillus sakei, Enterococcus faecium, Enterobacteriaceae* and yeasts proliferation at the end of the shelf-life period (Geeraerts et al., 2020). High extrusion temperature can lower the microbial load in PBMA.

However, potential virulence factors, infections, antibiotic resistance and gene transfer should be considered. Thus, kit manufacturers and organizations such as the Association of Official Agricultural Chemists (AOAC) International must validate diagnostic tests for screening pathogens. The higher temperatures and mechanical energy in extrusion processing may inadvertently lead to undesired chemical residues. More scientific evidence is still needed in this regard (MCS-Associates, 2022), as well as about the frequency of mycotoxins (Caldwell, 2021) and alkaloids. For instance, the prevalence of tentoxin (TEN) was found to be 0.3-1.6 µg/kg in soy/soy-based, chickpea/chickpea-based and pea/pea-based foods in the UK between 2010 and 2015. Similarly, consumption of pea-based burgers and soy- and wheat-based steak may lead to a non-tolerable exposure to alternariol (Hazard Index > 1) and ochratoxin A to liver and renal cancer (Margin of Exposure < 10,000) (Augustin Mihalache et al., 2023). Other safety challenges can relate to additives, with risks to clean labelling and consumer confidence (Kumar et al., 2022). With more than 2,000 proteins recognized as allergens, it is hard to predict the effect of regular consumption of higher protein concentrations and consumption of proteins from novel sources as well as the effect of new processing methods - namely, profilins, storage proteins and pathogenesis-related proteins, which elicit IgE-mediated immunological reactions (López-Pedrouso et al., 2023), gluten intolerance, handling and storage conditions after processing (Ishaq et al., 2022). Anti-nutrients, namely, protease inhibitors, α-amylase inhibitors, lectins, tannins, phytic acid, and carcinogens produced by high-temperature processing, such as polycyclic aromatic hydrocarbons, nitrosamines and heterocyclic aromatic amines, as well as heavy metal contaminants, namely, arsenic (As), cadmium (Cd), lead (Pb), nickel (Ni) and mercury (Hg), may be present in upcycled plant proteins, seaweeds and PBMAs at every stage (He et al., 2020; Hadi & Brightwell, 2021). Food safety should come first to make the industry viable.

A complete understanding of potential safety-relevant contaminants and nutritional quality associated with plant protein-based analogue products are the key elements to provide safe and nutritious food for the achievement of the United Nations (UN) Sustainable Development Goals (SDG) “Zero Hunger”, “Good Health and Well-being”, “Clean Water and Sanitation”, and “Responsible Production and Consumption”. Despite in-depth investigations into their extraction, processing, functional, and sensorial properties, the current knowledge and evidence on the safety and nutritional quality remain remarkably limited for food governing authorities (Mehdizadehtapeh et al, 2026).

## Future Perspectives

The future of alternative proteins hinges on overcoming existing sensory and nutritional limitations to achieve true market parity with conventional animal-based foods. The industry is evolving beyond simply offering vegetarian options, now striving to develop hyper-realistic, cost-effective meat and dairy analogues through advanced biotechnology, precision fermentation, and artificial intelligence (Kirtil, 2025). Several key advancements are expected to shape this trajectory, including improvements in texture and flavor, enhanced nutritional profiles, clearer regulatory frameworks and labeling standards, and the attainment of price parity (Su et al., 2024; Talwar et al., 2024; Cochlar et al., 2026).

## Conclusion

The emerging novel alternative proteins, meat and dairy analogues already contribute to such a transition; however, many challenges remain. Although some of these alternatives, including soy, tempeh, Quorn, seaweed and edible insects, have a long history of use, the current situation is new and unprecedented in scale and urgency. From plant-based substitutes to high-tech solutions used in cultured meat and precision fermentation, to mycoproteins, algae and edible insects, consumers are hesitant and demand transparency and reassurance about the health, safety and environmental benefits of the novel proteins, meat and dairy analogues. This study reveals that for the fourth industrial revolution in food production to successfully drive a protein transition, consumers must be engaged from the outset — including in the marketing of new products — to prevent rejection and resistance to dietary change. Hence, clear and compelling communication is needed to explain why and how novel proteins, meat and dairy alternatives surpass direct plant-based options, which have long offered significant benefits and remain a reliable and satisfying food choice.

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